6.0 SENSOR PERFORMANCE

6.1 Introduction

This section presents the performance evaluation for various sensors which might be used to meet the broad requirements for the functions of approach and landing aid, roll-out and taxi guidance, and high ground avoidance. The sensors considered here are radar and optical devices which would be suitable for installation in a commercial transport aircraft. Typical equipment parameters and space restrictions related to such an installation are included in hardware considerations.

Radar sensors which operate at X-band (10GHz), Ku band (16GHz), Ka band (35GHz) and V band (70GHz) are considered. These radars are evaluated for their ability to detect runways, with and without enhancement, to detect high ground, and to perform other specific functions. Meteorological attenuation due to rain and fog is a primary factor in the evaluation.

Optical sensors are included for both the visible region, 0.5 to 1.0 microns, and the infra-red region near 10 microns. These are the spectral regions in which extensive development work has been performed recently for low-light-level television and infra-red equipments for military applications. This choice was deliberate so that meaningful performance estimates could be promptly followed by the application of state-of-the-hardware techniques to a proof-of-concept demonstration system.

6.2 Radar, General Background

At V band frequencies it is possible to achieve narrow beamwidth and excellent resolution with a relatively small antenna that will fit in the limited space available in the nose of a typical transport aircraft. Therefore, a first supposition might be that the requirements for an IALM are best met with a radar operating at V band. However, the very high attenuation experienced in rain and fog and the large back-scatter effects produced from precipitation at V-band seriously affect performance. At lower frequencies the effect of fog and rain on performance is not so serious, but the angular resolution is degraded because of the necessarily wider azimuth beamwidth. There is, therefore, an optimum frequency and, in order to determine this, detailed assessments are made of the performance of radars operating on X, Ku, Ka, and V frequency bands. It is assumed that the precise Ka and V-band frequencies are chosen so as to minimize the oxygen plus water vapor absorption. It is further assumed that oxygen absorption will not be a key factor in choosing among the frequency bands once the absorption is minimized. The oxygen absorption characteristic is illustrated in Section 3 of Volume III.

6.2.1 Initial Assumptions About Equipment Characteristics. - So that a meaningful comparison can be made of the performance of radars operating in the various frequency bands, it is necessary to define equipment parameters. A very critical one is the antenna aperture; this should be as wide as possible, especially in the azimuth plane, in order to make the azimuth beamwidth narrow. But to make the antenna suitable for installation in the majority of civil aircraft, the maximum horizontal dimension must be set at something like 1 meter. This is the number which has been assumed for this report. However, in order to assess the performance of systems suitable for installation in the smaller and larger commercial aircraft, sensors with antennas having horizontal dimensions of 0.5 and 1.5 meters are also briefly considered. As regards the maximum vertical dimension of the antenna, it is assumed that this can be as much as 30 cms. Full advantage of this dimension is not taken with the Ka and V-band radars since, for beamwidths wide enough to give adequate coverage in the vertical plane, the apertures can be reduced to 15 cms and 8 cms, respectively.

To keep equipment size and weight down to a reasonable level, a peak transmitter power of 20 kW has been assumed. At V-band, the peak power is 10 kW, since this is the maximum available from existing magnetrons.

Both the IALM and HGA systems require good angular accuracy in the elevation plane and to achieve this capability a monopulse (Ref.24) or interferometer system (Ref.25) has to be used. In this report the calculations are based on the assumption that the monopulse feature would be used, but the conclusions regarding the optimum frequency band would also apply to an interferometer system.

The X-band radar considered in this study is assumed to be horizontally polarized. Extrapolation from available back scattering coefficient data (Ref.26) shows that horizontal as compared with vertical polarization presents a greater relative difference between the returns received from grass and those received from concrete, and thus, is a better choice for runway detection. The Ku, Ka, and V-band radars are assumed to be circularly polarized in order to reduce the effects of back scatter from rain; a rain echo cancellation figure of 15 dB has been assumed (Ref.27).

The receiver noise figures assumed include waveguide losses and are typical of those that would be obtained in the field with present day equipments.

Table II-26 lists the parameters assumed for the various radar equipments. Since, in certain cases, the performance varies considerably with the transmitter pulse width, calculations have been made with pulse widths of 1.0, 0.5 and 0.1 microseconds.

TABLE II-26. PARAMETERS OF RADAR EQUIPMENTS

Parameter	Frequency Band			
	X 10GHz	Ku 16GHz	Ka 35GHz	V 70GHz
Transmitter Power, kW	20	20	20	10
* Azimuth Beamwidth	2.5°	1.5°	0.7°	0.35°
Elevation Beamwidth	7.5°	4.5°	4.0°	4.0°
Polarization	Horizontal	Circular	Circular	Circular
Antenna Gain	2100	5900	14,400	28,800
Noise Figure, dB	10	12	16	25
Pulse Widths, μs	1.0,0.5,0.1	1.0,0.5,0.1	1.0,0.5,0.1	1.0,0.5,0.1

* (1 m aperture)

6.2.2 Initial Assumptions About Environmental Characteristics. - It is, of course, essential for the HGA and IALM radar to work satisfactorily in fog and rain where performance, especially at the higher frequency bands, can be seriously affected. Calculations have, therefore, been made of the effect on performance of 400 ft. and 100 ft visibility fog and of rainfall densities of 1, 4 and 16 mm/hr. Although rainfall densities well in excess of 16 mm/hr can occur in heavy showers and/or in particular geographical regions, it has been concluded that this happens only on a small percentage of occasions and that the showers generally do not extend over a long distance. Consequently, rainfall rates in excess of 16 mm/hr are regarded in this study as representative of only a minor percentage of transport operating experiences.

The figures commonly used for attenuation in fog and rain are the theoretical values (Ref. 8), the derivation of these is discussed in Section 3 , Vol. III. Experimental measurements of attenuation through rainfall give results which are not always equal to the theoretical values (Ref.28). However, these results vary over wide limits and furthermore, are not available for all frequency bands.

The relationship between visibility in fog and water vapor content usually adopted is the empirical one (Ref.29), in which the attenuation is stated to be directly proportional to the water content, i.e. . . . . (*)

$$\bar{M} = 1660/d^{1.43}$$

where d = optical visibility in feet

M = average moisture content in grams/meter^3

This equation is used to give the "theoretical" attenuation in fog of various levels of obscuration. The equation gives a moisture content of 2.3 g/m^3 in fog characterized as 100 ft visibility fog. A moisture content of 0.83 g/m^3 is postulated for 200 ft visibility fog. But Dickson and Hales (Ref.30) give a water content of only 0.412 g/m^3 corresponding to a visibility of 200 ft. Matveev (Ref.31) also states that the maximum liquid water content of thick fog is 0.76 g/m^3. One can deduce, therefore, that the "theoretical" fog attenuation figures are pessimistic and, in practice, that the attenuation could be less than half the calculated value.

Since there are no practical attenuation figures that are universally accepted, we have based our calculations primarily upon the "theoretical" values adopted by radar engineers; these are listed in Table II-27. Although in practice the performance may differ from that predicted, a comparison of the relative performance with the different frequency bands will allow the optimum band to be chosen.

Another weather condition which must be considered is snow. The expression given by Gunn and East (Ref. 8) for the attenuation in snow shows that at X, Ku and Ka frequency bands, the attenuation is well below that of rain of equal water content. This also applies at V-band, except when the precipitation rate is equivalent to 16 mm/hr; in this case the attenuation in snow is shown to be approximately equal to that of the equivalent rainfall. Since the visibility in snow is poor, it is of interest to compare the attenuation in snowfall equivalent to 16 mm/hr with that of the attenuation experienced in 100 ft visibility fog. The attenuation of snow of this density is 0.014, 0.21, 0.51 and 5.8 dB/km (one way) for X, Ku, Ka and V-bands, respectively. A comparison with the figures for 100 ft fog given in Table II-27 shows that as regards attenuation, a system that operates satisfactorily in 100 ft fog should also operate satisfactorily in snowfall with a liquid content equal to 16 mm/hr. It should be noted that these theoretical attenuation values may be twice the typical values observed in practice. Also, fog at 0° has greater attenuation than the values shown here but its probability of occurrence was judged to be small.

(*) More recently Eldridge (Ref.1) has stated that the empirical relationship ($\bar{M} = 950/d^{1.54}$) gives results which agree with measurements, and with this value, the moisture content for 100 ft visibility fog is 0.8 gm/cm^3.

TABLE II-27. RAIN AND FOG ATTENUATION (dB/km, one-way)--THEORETICAL VALUES FOR 18°C.

Frequency Band	Rainfall Rates			Fog Densities	
	1 mm/hr	4 mm/hr	16 mm/hr	100 ft visibility	400 ft visibility
X	0.01	0.05	0.26	0.1	0.02
Ku	0.07	0.25	1.28	0.36	0.08
Ka	0.30	1.07	4.07	1.39	0.27
V	0.80	2.40	7.30	5.12	0.72

As discussed in Section 4, Vol. III, the back scatter from rain also affects performance by producing false signals. The amplitude of the echo is determined by the scattering cross section per unit volume and the theoretical values of this for various rainfall densities (Ref. 8) are listed in Table II-28 below.

Measurements at S-band show that the scattering coefficient is 4 to 10dB below the theoretical value (Ref. 8) and there are indications that this effect is also experienced at higher frequencies. However, in the absence of accepted empirically derived figures, we have used the theoretical values to make a comparison of performance obtained with radars operating at four different frequency bands.

TABLE II-28. RADAR CROSS SECTION (m^2/m^3) OF RAIN AT 18° C

Frequency Band	Rainfall Rates		
	1 mm/hr	4 mm/hr	16mm/hr
X	1.3×10^{-7}	1.0×10^{-6}	9×10^{-6}
Ku	1.3×10^{-6}	1.1×10^{-5}	6×10^{-5}
Ka	1.8×10^{-5}	1.3×10^{-4}	6×10^{-4}
V	2.6×10^{-4}	1.9×10^{-3}	8.7×10^{-3}

This table also applies to attenuation experienced due to back scatter on dry snow which has a liquid content equal to that of rain (Ref. 8).

The hydrometeors having the largest scattering cross sections are water-coated ice spheres, hail, which produce a so called "bright band". This band forms under special atmospheric conditions when the temperature is just above $0^{\circ}C$, and is only a few hundred feet in vertical extent. It has a scattering cross section of up to 10 dB greater than that of rain of equal water content. However, at maximum range where the effect of this unique return could be most serious, the "bright band" will, in general, occupy only a fraction of the total vertical beamwidth and, consequently, its echo will not be greater than that received from the rain under it. Its special effect, therefore, is disregarded in calculations of attenuation.

6.2.3 Initial Assumptions About Target Signatures. - The performance of an IALM depends upon the signals scattered back from ground at grazing angles as low as 3°. Data appearing in Section 2, Vol. III, shows that very few measurements have been made of the scattering coefficient of various terrains at grazing angles of less than 10°. Extrapolation of existing curves to 3° gives values which are probably reasonably accurate at X and Ku-band frequencies but may be misleading at Ka-band. No results are available for V-band.

The ability of a mapping radar to detect and display an airport runway depends upon the difference between the scattering coefficient of the runway and that of the adjacent ground. The Ohio State University Terrain Handbook (Ref.26) shows that at a 10° grazing angle the scattering coefficient of grass is about 20 dB above that of concrete and 10 dB above that of asphalt. In the absence of any empirical measurements, it is assumed that these figures hold, down to 3° grazing, for the four frequency bands. In reality, the scattering characteristic may rise sharply as the angle is reduced to very small values. This possibility is affected by the type of polarization. It is also realized that at Ka and V-bands the surface roughness of runways is becoming large compared with the wavelength and, consequently, these assumptions may be incorrect. However, the good mapping pictures of airports obtained with Ka-band Airport-Surface Movement Radar Systems show that there is a satisfactory ratio at low grazing angles with this band.

The absolute scattering coefficient of the grass adjacent to the runway will vary from airport to airport depending upon length of grass, dryness of ground, frequency band, etc. For 2-inch grass, extrapolation of the Ohio State University results to 3° incidence angle indicates that the value for X, Ku, and Ka-bands is approximately - 13 dB. Therefore, this figure has been assumed for all frequency bands.

6.2.4 Methodology. - The approach adopted in estimating the radar performance is to define the requirements to meet a given task in terms of a number of signal ratios, for example, terrain signal to noise, terrain signal to rain, etc. Equations giving these ratios are derived in Sections 5, 6 and 7 of Vol. III for the various frequency bands and for different weather conditions. The ranges at which all the requirements are met are derived from these data. Although the ratio values adopted for the various requirements are subject to argument, it is considered that they give a realistic indication of the performance that would be obtained in practice.

In addition to calculating performance using the "theoretical" figures for attenuation of rain and fog, an estimate is also made of that obtained with the less pessimistic "typical" figures observed in practice. This will give a more realistic indication of in-service performance, but it should be treated with some caution because the attenuation and back scatter figures used are not universally accepted.

6.3 Radar Detection of Runways

6.3.1 Non-Cooperative Environment. - For a radar carried by an aircraft to have a landing monitor capability, it must be able to measure the aircraft's position and direction relative to the glide path. Glide Slope Monitoring satisfies the conceptual ILM requirement, but in reality the ILM would also predict and display the touchdown point as a desirable added capability. The simplest way of providing the monitoring capability is with a forward looking ground mapping radar which displays a map of the airport having sufficient definition for the pilot to be able to identify the runway and its threshold, together with an indication of aircraft track and distance to go. The advantage of this method is that it does not require any aids, either passive or active, on the ground.

It is also desirable for the radar to have means for measuring the aircraft's position with respect to the glide slope in the elevation plane. As will be shown in Section 6.3.3, this can be achieved, with a radar having monopulse or an interferometer capability in the vertical plane, by pitch stabilizing the boresight so that it is depressed below the horizontal by the amount of the glide path angle, and indicating on the display where the boresight intercepts the ground. The aircraft is on the glide slope when this intercept falls within the desired touchdown area.

A radar is able to detect runways because of the difference between the scattering coefficients of the runway surface and the adjacent ground. However, it should be noted that when the airport is covered with snow, this difference disappears and runways may not be detected. There are numerous airports with concrete or asphalt between the runways and this feature also makes it impossible for the runways to be identified. Because of these limitations, a strong case can be made for a system which does not rely entirely upon signals back scattered from the surface of the airport but rather employs radar

reflectors or transponder beacons, suitably placed on the ground, to indicate runway position. These systems are discussed later on in the report.

(A) Visibility of Runway on a Display

Signal Level and Azimuth Beamwidth. - At a range 7 to 10 nm from runway threshold, which is the primary system range design requirement as established in Section 4, the display should indicate the line of the runway, and at ranges of 5 nm and less, the stated objective is to identify both the touchdown point and the intercept of the flight vector with the ground. Information should be available down to a minimum range which depends upon the landing category to be met. It is difficult to lay down precise minimum signal level and azimuth beamwidth conditions that will achieve this, since so much depends upon operator skill and adjustment of the equipment. Recall, too, that capabilities are described with respect to a 1-meter aperture. But in order to compare the performance of radars on different frequency bands, it is necessary to have standard conditions; therefore, for the purpose of this report, it has been assumed that the following requirements are to be met.

Requirements*

a) Azimuth beamwidth narrow enough to allow the pilot to align flight vector to center-line of runway to within 0.40°.

b) A drop in signal amplitude of more than 3 dB as the radar beam sweeps through the runway.

c) Signal from terrain adjacent to runway to be greater than 10 dB above receiver noise.

d) Signal from terrain adjacent to runway to be greater than 10 dB above that from rain at the same range.

In order to establish required runway direction relative to actual aircraft track, the radar must detect and display a reasonable portion of the runway. The amount required depends upon the picture quality but it is likely to be between 1/2 and 1 nm.

o X Band Radar. - In practice it has been found possible when using a display to estimate angular position to within one quarter toone half of the azimuth beamwidth. Since the X-band radar has an azimuth beamwidth of 2.5°, Requirement (a) is not met and it is, therefore, not considered suitable for an unassisted landing monitor for approaches to runways 150 feet in width.

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* These requirements are referred to by letters (a) through (d) in the following text and tables.

To obtain acceptable performance with an X band radar without resorting to runway enhancement techniques to improve resolution, the antenna aperture would have to be increased to 1.7m which is too large for an airborne antenna in most current aircraft nose and radome installations. This would give the same detection ranges as those listed in the following paragraph for the Ku band radar with a 1-meter antenna, with the exception that there would be no reduction in range with 16mm/hr rainfall. This is due to the radar cross-section of rain being much less at X band.

o Ku-Band Radar. - Requirement (a) is marginally met with the Ku-band radar having an azimuth beamwidth of 1.5°.

As regards Requirement (b), from Figures III-28 and III-29, Section 5, Volume III, we obtain the following ranges for the detection of 300 ft. wide concrete and asphalt runways. The ranges are halved with 150 ft. wide runways.

TABLE II-29. RANGE (nm)* AT WHICH RUNWAY CAN BE IDENTIFIED ON A DISPLAY OF THE Ku BAND RADAR -- Requirement (b)

Runway Width	Concrete	Asphalt
150 ft.	2.2 (4.1)	2.0 (3.6)
300 ft.	4.4 (8.1)	3.9 (7.2)

It should be noted that as the range to runway is decreased, there is a rapid improvement in the ability of the radar to detect runways. At a range of 3 nm the change in signal as the beam sweeps through a 300 ft concrete runway has increased to 5 dB.

From the calculations made in Section 6, Volume III, the following tables listing the maximum ranges for Requirements (c) and (d), i.e. Terrain Signal/Noise greater than 10dB and Terrain Signal/Rain Echo greater than 10dB, are obtained.

TABLE II-30. RANGE (nm)* AT WHICH TERRAIN SIGNAL/NOISE RATIO HAS FALLEN TO 10 dB -- Requirement (c)

Pulse Length	Rainfall Rates				Fog Densities	
μ sec	0 mm/hr	1 mm/hr	4 mm/hr	16 mm/hr	400 ft	100 ft
1.0	70 (130)	37 (68)	19 (35)	6.5 (12)	32 (60)	15 (28)
0.5	44 (82)	27 (50)	15 (28)	5.9 (11)	24 (45)	12 (22)
0.1	15 (28)	12 (33)	8.1 (15)	3.8 (7)	11 (21)	7.0 (13)

* Ranges are given both in nm and km (kilometers in parentheses)

TABLE II-31. RANGE (nm)* AT WHICH TERRAIN SIGNAL/RAIN ECHO RATIO HAS FALLEN TO 10 dB WITH CIRCULAR POLARIZATION -- Requirement (d)

Rainfall, mm/hr	Range, nm (km)*
1	42 (77)
4	5.3 (9.8)
16	0.8 (1.5)

From Tables II-29, 30 and 31, the following table has been produced which lists the maximum range at which the Requirements (b), (c) and (d) are all satisfied. The Requirement that is limiting the range is given in the form of a lower case letter code immediately following each range entry in the table.

TABLE II-32. RANGE (nm)* AT WHICH THE Ku BAND RADAR DETECTS RUNWAYS

Runway	Pulse Length	Rainfall Rates				Fog Densities	
	μ sec	0 mm/hr	1 mm/hr	4 mm/hr	16 mm/hr	400 ft	100 ft
150 ft Concrete	1.0	2.2 (4.1) b	2.2 (4.1) b	2.2 (4.1) b	0.8 (1.5) d	2.2 (4.0) b	2.2 (4.0) b
	0.5	2.2 (4.1) b	2.2 (4.1) b	2.2 (4.1) b	0.8 (1.5) d	2.2 (4.0) b	2.2 (4.0) b
	0.1	2.2 (4.1) b	2.2 (4.1) b	2.2 (4.1) b	0.8 (1.5) d	2.2 (4.0) b	2.2 (4.0) b
300 ft. Concrete	1.0	4.4 (8.1) b	4.4 (8.1) b	4.4 (8.1) b	0.8 (1.5) d	4.4 (8.1) b	4.4 (8.1) b
	0.5	4.4 (8.1) b	4.4 (8.1) b	4.4 (8.1) b	0.8 (1.5) d	4.4 (8.1) b	4.4 (8.1) b
	0.1	4.4 (8.1) b	4.4 (8.1) b	4.4 (8.1) b	0.8 (1.5) d	4.4 (8.1) b	4.4 (8.1) b
150 ft. Asphalt	1.0	2.0 (3.6) b	2.0 (3.6) b	2.0 (3.6) b	0.8 (1.5) d	2.0 (3.7) b	2.0 (3.7) b
	0.5	2.0 (3.6) b	2.0 (3.6) b	2.0 (3.6) b	0.8 (1.5) d	2.0 (3.7) b	2.0 (3.7) b
	0.1	2.0 (3.6) b	2.0 (3.6) b	2.0 (3.6) b	0.8 (1.5) d	2.0 (3.7) b	2.0 (3.7) b
300 ft. Asphalt	1.0	3.9 (7.2) b	3.9 (7.2) b	3.9 (7.2) b	0.8 (1.5) d	3.9 (3.9) b	3.9 (3.9) b
	0.5	3.9 (7.2) b	3.9 (7.2) b	3.9 (7.2) b	0.8 (1.5) d	3.9 (3.9) b	3.9 (3.9) b
	0.1	3.9 (7.2) b	3.9 (7.2) b	3.9 (7.2) b	0.8 (1.5) d	3.9 (3.9) b	3.9 (3.9) b

* Ranges are given both in nm and km (kilometers in parentheses)

** Limiting Requirements are designated by lower case letters in each column.

This table shows that Requirement (b), change in signal amplitude of 3 dB, is the main limitation (See: Sec. 6.3.1.A); performance with respect to 300 ft. wide runways is marginally acceptable but the range is far too short for operation into 150 ft. runways. Of course, if the azimuth beamwidth could be reduced by increasing the antenna aperture, there would be marked improvement in performance.

An antenna horizontal aperture of 1m is the minimum that can be used with the Ku band radar if the specified azimuth angular accuracy is to be met. Increasing the aperture to 1.5m would reduce the azimuth beam-width to 1° and runway detection range in 100ft visibility fog would increase to over 3nm for 150ft runways and to over 6nm for 300ft runways. These ranges would be maintained in rainfall densities of up to 4mm/hr, but with 16mm/hr rainfall, the backscatter would reduce the detection range to a very low value.

o Ka-Band Radar. - Requirement (a) is easily met with the Ka band radar since a one-meter aperture yields a 0.7° azimuth beamwidth.

From Section 5, Vol. III, we obtain the following table giving the range at which the runway is detected on the display.

TABLE II-33. RANGE (nm) * AT WHICH RUNWAY IS DETECTED ON A DISPLAY WITH Ka BAND RADAR --- Requirement (b)

Runway Width	Concrete	Asphalt
150 ft	4.8 (8.9)	4.3 (7.9)
300 ft	9.6 (17.8)	8.5 (15.7)

The ranges at which the Terrain Signal/Noise and Terrain Signal/Rain Echo ratios are 10 dB, are given in Tables III-13 & 14 (Vol. III) and are listed below, with the ranges expressed in nautical miles.

TABLE II-34. RANGE (nm) * AT WHICH TERRAIN SIGNAL/NOISE RATIO HAS FALLEN TO 10 dB --- Requirement (c)

Pulse Length (μ sec)	Rainfall Rates				Fog Densities	
	0 mm/hr	1 mm/hr	4 mm/hr	16 mm/hr	400 ft	100 ft
1.0	43 (80)	12 (23)	6.5 (12)	2.4 (4.5)	14 (26)	5.1 (9.5)
0.5	25 (47)	10 (20)	5.2 (9.6)	2.2 (4.0)	11 (20)	4.3 (8.0)
0.1	14 (26)	5.4 (10)	3.2 (6.0)	1.5 (2.7)	5.9(11)	2.7 (5.0)

* Ranges are given both in nm and km (kilometers in parentheses)

TABLE II-35. RANGE (nm) * AT WHICH TERRAIN SIGNAL/RAIN ECHO RATIO HAS FALLEN TO 10 dB WITH CIRCULAR POLARIZATION
--- Requirement (d)

Rainfall, mm/hr.	Range, nm.*
1	3.2 (5.9)
4	0.5 (0.93)
16	0.1 (0.19)

The maximum range at which Requirements (b), (c) and (d) are all met are listed in Table II-36.

TABLE II-36. RANGE (nm)* AT WHICH THE Ka BAND RADAR DETECTS RUNWAYS

Runway	Pulse Length	Rainfall Rates				Fog Densities	
	μ sec	0 mm/hr	1 mm/hr	4 mm/hr	16 mm/hr	400 ft	100 ft
150 ft. Concrete	1.0	4.8 (8.9) b	3.2 (5.9) d	0.5 (0.9) d	0.1 (0.2) d	4.8 (8.9) b	4.8 (8.9) b
	0.5	4.8 (8.9) b	3.2 (5.9) d	0.5 (0.9) d	0.1 (0.2) d	4.8 (8.9) b	4.3 (8.0) c
	0.1	4.8 (8.9) b	3.2 (5.9) d	0.5 (0.9) d	0.1 (0.2) d	4.8 (8.9) b	2.7 (5.0) c
300 ft. Concrete	1.0	9.6 (17.8) b	3.2 (5.9) d	0.5 (0.9) d	0.1 (0.2) d	9.6 (17.7) b	5.1 (9.5) c
	0.5	9.6 (17.8) b	3.2 (5.9) d	0.5 (0.9) d	0.1 (0.2) d	9.6 (17.7) b	4.3 (8.0) c
	0.1	9.6 (17.8) b	3.2 (5.9) d	0.5 (0.9) d	0.1 (0.2) d	5.9 (11) c	2.7 (5.0) c
150 ft. Asphalt	1.0	4.3 (7.9) b	3.2 (5.9) d	0.5 (0.9) d	0.1 (0.2) d	4.3 (7.9) b	4.3 (7.9) b
	0.5	4.3 (7.9) b	3.2 (5.9) d	0.5 (0.9) d	0.1 (0.2) d	4.3 (7.9) b	4.3 (7.9) b
	0.1	4.3 (7.9) b	3.2 (5.9) d	0.5 (0.9) d	0.1 (0.2) d	4.3 (7.9) b	2.7 (5.0) c
300 ft. Asphalt	1.0	8.5 (15.7) b	3.2 (5.9) d	0.5 (0.9) d	0.1 (0.2) d	8.5 (15.7) b	5.1 (9.5) c
	0.5	8.5 (15.7) b	3.2 (5.9) d	0.5 (0.9) d	0.1 (0.2) d	8.5 (15.7) b	4.3 (8.0) c
	0.1	8.5 (15.7) b	3.2 (5.9) d	0.5 (0.9) d	0.1 (0.2) d	5.9 (11) c	2.7 (5.0) c

With an antenna aperture of 0.5m, suitable for installation in the smaller commercial aircraft, the detection ranges would be reduced to those listed on Pages 89, 90 and 91 for the Ku band radar with a 1m antenna, except in rainfall of 4mm/hr and above. With rainfall of this density, the larger cross-section at Ka band would limit the range to below 0.5 nautical miles.

Note: ** Limiting Requirements are designated by lower case code letters in each column.
* Ranges are given both in nm and km (kilometers in parentheses).

An antenna with an aperture of 1.5m, suitable for installation in the larger commercial aircraft, would not give greater detection ranges in rain than those with a 1m antenna. In 100ft visibility fog, there would be a very small increase in range, but in 400ft fog, the range on 100ft runways with a 1μ s transmitter pulse would be greater than 10nm.

o V Band Radar. - The azimuth beamwidth of the V band radar is 0.35°; hence Requirement (a) is easily met.

As regards Requirement (b), no information is available on scattering coefficients at V-band but it is probable that the grass/runway ratio is smaller than is the case at lower frequencies. However, in the absence of empirical evidence, it is assumed to be the same.

From Section 5, Vol. III, the following table is obtained which lists the maximum range at which the runway is detected on the display.

TABLE II-37. RANGE (nm)* AT WHICH RUNWAY IS DETECTED ON A DISPLAY WITH THE V-BAND RADAR ** --- Requirement (b)

Runway Width	Concrete	Asphalt
150 ft.	9.7 (18)	8.6 (16)
300 ft.	19 (35)	17 (31)

From Section 6, Volume III, the following tables are obtained which list the ranges at which the Terrain Signal/Noise and Terrain Signal/Rain Echo ratios are 10 dB.

TABLE II-38. RANGE (nm)* AT WHICH TERRAIN SIGNAL/NOISE RATIO HAS FALLEN TO 10 dB ** --- Requirement (c)

Pulse Length	Rainfall Rates				Fog Densities	
μ sec	0 mm/hr	1 mm/hr	4 mm/hr	16 mm/hr	400 ft	100 ft
1.0	14 (26)	4.5(8.3)	2.5(4.7)	1.2(2.2)	5.0(9.2)	1.5(2.8)
0.5	8.6(16)	3.6(6.6)	2.1(3.9)	1.0(1.9)	4.0(7.4)	1.3(2.4)
0.1	3.0(5.5)	1.9(3.5)	1.3(2.4)	0.7(1.3)	2.2(4.0)	0.9(1.6)

** Limiting Requirements are designated by lower case letters in each column.

* Ranges are given both in nm and km (kilometers in parentheses)

TABLE II-39. RANGE (nm)* AT WHICH TERRAIN SIGNAL/RAIN ECHO RATIO HAS FALLEN TO 10 dB WITH CIRCULAR POLARIZATION
--- ** Requirement (d)

Rainfall, mm/hr	Range, nm (km) *
1	0.25 (0.47)
4	0.032 (0.06)
16	0.008 (0.015)

The maximum range at which Requirements (b), (c) and (d) are all met are listed in Table II-40

TABLE II-40. RANGE (nm)* AT WHICH THE V-BAND RADAR DETECTS RUNWAYS **

Runway	Pulse Length	Rainfall Rates				Fog Densities	
	μ sec	0 mm/hr	1 mm/hr	4 mm/hr	16 mm/hr	400 ft	100 ft
150 ft Concrete	1.0	9.6 (18)b	0.25(.47)d	0.032(.06)d	.008(.015)d	4.9(9.2)c	1.5(2.8)c
	0.5	8.6 (16)c	0.25(.47)d	0.032(.06)d	.008(.015)d	3.8(7.4)c	1.2(2.4)c
	0.1	2.9 (5.5)c	0.25(.47)d	0.032(.06)d	.008(.015)d	1.9(4.0)c	0.9(1.6)c
300 ft Concrete	1.0	14.0 (26)c	0.25(.47)d	0.032(.06)d	.008(.015)d	4.9(9.2)c	1.5(2.8)c
	0.5	8.6 (16)c	0.25(.47)d	0.032(.06)d	.008(.015)d	3.8(7.4)c	1.2(2.4)c
	0.1	2.9 (5.5)c	0.25(.47)d	0.032(.06)d	.008(.015)d	1.9(4.0)c	0.9(1.6)c
150 ft Asphalt	1.0	8.5 (16)b	0.25(.47)d	0.032(.06)d	.008(.015)d	4.9(9.2)c	1.5(2.8)c
	0.5	8.5 (16)b	0.25(.47)d	0.032(.06)d	.008(.015)d	3.8(7.4)c	1.2(2.4)c
	0.1	2.9 (5.5)c	0.25(.47)d	0.032(.06)d	.008(.015)d	1.9(4.0)c	0.9(1.6)c
300 ft Asphalt	1.0	14.0 (26)c	0.25(.47)d	0.032(.06)d	.008(.015)d	4.9(9.2)c	1.5(2.8)c
	0.5	8.6 (16)c	0.25(.47)d	0.032(.06)d	.008(.015)d	3.8(7.4)c	1.2(2.4)c
	0.1	2.9 (5.5)c	0.25(.47)d	0.032(.06)d	.008(.015)d	1.9(4.0)c	0.9(1.6)c

The detection range of the V band radar is limited by the attenuation in rain and fog and not by the azimuth beamwidth. In fact, the azimuth beamwidth could be increased to 0.7°, by a reduction in the aperture size to 0.5m, without there being any appreciable change in the detection range in rain and fog.

** Limiting Requirements are designated by lower case letters in each column.

* Ranges are given both in nm and km (kilometers in parentheses)

Increasing the aperture to 1.5m would improve the definition of the ground mapping picture, but the range in rain and fog would not be significantly altered. Table II-40 clearly shows that the performance of the V Band radar is seriously degraded in rain and fog.

o Optimum Frequency Band for Detection of Runways. - Table II-41 shows runway detection performance, under various weather conditions, of radars operating on X, Ku, Ka and V frequency bands, each of which utilizes a 1 meter antenna.

Because of its narrow beamwidth, the V-band radar is seen to have excellent performance in clear weather. But in theory the range in rain and fog will be drastically reduced. It can be argued that reduction of range in rain is not serious since visibility remains reasonably good and, hence, there is no requirement for a landing monitor. The equipment must, however, work satisfactorily in fog but Table II-41 shows that in 100 ft. visibility fog the maximum range from threshold at which a runway is detected is only 1.5 nm with a pulse length of 1.0 μs. The detection range is smaller if "detection" implies that a significant length of runway is being observed. It has already been mentioned that the attenuation figures assumed for fog may be pessimistic. If the water content in 100 ft visibility fog turns out to be half the assumed value, the maximum detection range increases from 1.5 to 2.3 nm.

At Ku-band, the range at which one mile of runway will be perceived is limited by the azimuth beamwidth to between 1 and 3.4 nm from threshold, depending upon the runway composition and its width, in all weather conditions except 16 mm/hr rain.

With the constraints on the antenna aperture and transmitter power, the optimum frequency band for best performance in fog is that at which Requirements (b) and (c) are met at the same range. Examination of the Ka band performance figures for 100 ft. fog shows that the requirement responsible for the limitation in range changes from attenuation to angular discrimination, depending upon the runway width. Hence, for a radar that has to deal with both runway widths, Ka is the optimum frequency band. With a transmitter pulse length of 1.0 μs the range varies from 3 to 4.4 nm depending upon the runway surface and its width. The range capability increases to 7 nm for 300 ft runways assuming 'typical' attenuation in 100 ft. fog.

The maximum range of the Ku band radar is not affected by the transmitter pulse length. But reducing the pulse length of the Ka and V-band radars reduces the maximum range. For a system to work in a 100 ft. visibility fog, the radar minimum range should also be 100 ft and this requires a pulse length of 0.1 μs. Similarly, the pulse length of the radar to cater to a minimum visibility of 400 ft. should not exceed 0.5 μs. Applying these conditions, the maximum range in a 100 ft. fog on a 150 ft. concrete runway is 2.9 nm and 0.9 nm, respectively for Ka and V-bands. The radar with a 400 ft. minimum visibility would have a maximum range, in 400 ft. fog on a 150 ft. concrete runway, of 4.8 nm and 3.8 nm, respectively, for the Ka and V-bands.

TABLE II-41. A SUMMARY OF DETECTION RANGES FOR UNENHANCED RUNWAYS

Runway Width and Material	Pulse Width μs	Rainfall Rates												Fog Densities					
		0 mm/hr			1 mm/hr			4 mm/hr			16 mm/hr			400 ft			100 ft		
150' Concrete	1.0	2.2	4.8	9.6	2.2	3.2	0.25	2.2	0.5	0.032	0.8	0.1	0.008	2.2	4.8	4.9	2.2	4.8	1.5
	0.5	↓	↓	8.6	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	3.8	↓	4.3	1.2
	0.1	↓	↓	2.9	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	1.9	↓	2.7	0.9
300' Concrete	1.0	4.4	9.6	14	4.4	↓	↓	4.4	↓	↓	↓	↓	↓	4.4	9.6	4.9	4.4	5.1	1.5
	0.5	↓	↓	8.6	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	9.6	3.8	↓	4.3	1.2
	0.1	↓	↓	2.9	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	5.9	1.9	↓	2.7	0.9
150' Asphalt	1.0	2.0	4.3	8.5	2.0	↓	↓	2.0	↓	↓	↓	↓	↓	2.0	4.3	4.9	2.0	4.3	1.5
	0.5	↓	↓	8.5	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	3.8	↓	4.3	1.2
	0.1	↓	↓	2.9	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	1.9	↓	2.7	0.9
300' Asphalt	1.0	3.9	8.5	14	3.9	↓	↓	3.9	↓	↓	↓	↓	↓	3.9	8.5	4.9	3.9	5.1	1.5
	0.5	↓	↓	8.6	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	8.5	3.8	↓	4.3	1.2
	0.1	↓	↓	2.9	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	5.9	1.9	↓	2.7	0.9
		Ku	Ka	V	Ku	Ka	V	Ku	Ka	V	Ku	Ka	V	Ku	Ka	V	Ku	Ka	V
		FREQUENCY BAND																	

The effect that the size of the horizontal aperture of the antenna has on the detection range of runways is shown in Table II-42. This lists the ranges obtained in 400 ft. visibility fog with apertures of 0.5m, 1.0m and 1.5m, for transmitter pulse lengths of 1.0 μs and 0.5 μs.

TABLE II-42. VARIATION OF RUNWAY DETECTION RANGE WITH ANTENNA APERTURE

Antenna Aperture (m)	Runway Width (ft)	Runway Detection Range in 400 ft Fog					
		Ku Band		Ka Band		V Band	
		1.0μs	0.5μs	1.0μs	0.5μs	1.0μs	0.5μs
0.5	300 ft	0 0	0 0	4.4 (8.2)	4.4 (8.2)	4.5 (8.3)	3.5 (6.5)
	150 ft	0 0	0 0	2.2 (4.1)	2.2 (4.1)	4.5 (8.3)	3.5 (6.5)
1.0	300 ft	4.4 (8.1)	4.4 (8.1)	9.6 (17.7)	9.6 (17.7)	4.9 (9.2)	3.8 (7.4)
	150 ft	2.2 (4.0)	2.2 (4.0)	4.8 (8.9)	4.8 (8.9)	4.9 (9.2)	3.8 (7.4)
1.5	300 ft	6.0 (11.1)	6.0 (11.1)	15.0 (27.8)	11.0 (20.4)	5.2 (9.6)	4.0 (7.4)
	150 ft	3.0 (5.6)	3.0 (5.6)	10.0 (18.5)	10.0 (18.5)	5.2 (9.6)	4.0 (7.4)

The performance of the V-band radar is limited by the attenuation in the rain and fog and, as a result, the variation of detection range with aperture size is quite small. With both the Ku and Ka band radars the detection range increases with an increase in the size of the antenna aperture. If good performance in rain is not essential, the optimum frequency band for a radar with a 0.5m antenna is V band. But when space is available for a 1.5m antenna Ka is the optimum frequency band.

Table II-41 demonstrates that none of the frequencies considered provides for the 7 to 10 mile range desired. It is concluded, therefore, that direct observation of the unenhanced runway is not a promising concept, and that some form of runway enhancement is desirable.

* Ranges are given both in nm and km (kilometers in parentheses).

(B) Interference

o Causes of Interference. - For the radar to perform satisfactorily as a landing monitor, the display should not be obscured with interfering signals from other radars. A limited number of spurious returns will not be troublesome since the interference signals reveal themselves by moving about the display; however a continuous presentation of false signals or frequent presentation of a large number of interfering signals could make it very difficult to detect the runway.

The strongest form of interference occurs when the beams of two aircraft are pointed directly at each other. Table III-32, Volume III, summarizes an analysis for the ranges at which this kind of interference can occur. It shows that, in theory, at Ku band most aircraft within optical range could contribute to the creation of an interference pattern. The table also shows that, even in 100 ft visibility fog, interference can be generated over a range of 50 nm.

Signals transmitted by one aircraft and reflected from the ground into the radar receiver of a second aircraft can produce interference under certain conditions. Section 7 (Volume III) shows that the ratio of interference signal to desired signal has a maximum value when the range to the ground along the antenna boresight of the aircraft causing the interference is at its minimum value. The maximum value occurs just before the aircraft flares out for touchdown. Table III-33 of Section 7, Volume III, shows that with X and Ku bands operating in 100 ft visibility fog, aircraft out to 10 nm from touchdown could be subject to interference. Interference occurs only when the antenna beams intercept the same patch of ground and the interfering carrier frequency is within the receiver pass band.

With an azimuth beamwidth of β° and a sector scan of Φ°, the probability of the beams intercepting the same patch of ground is 1 in $(\Phi/\beta)^2$. Thus, with Ku-band radars having azimuth beamwidths of 1.5° and sector scans of 60°, the probability is one in 1600. The aircraft capable of producing interference are all those within a 10 nm radius of touchdown having a scan pattern which intersects that of the landing aircraft. The number of aircraft meeting these conditions is probably less than 10 and, consequently, the total probability of interference with the Ku-band radar is 1 in 160. It would be lower still with the Ka-band radar because of its narrower beamwidth.

The ranges over which side-lobe-to-side-lobe transmission of interference can occur is shown in Table III-31, Volume III. In the case of side-lobe transmission, the interference is independent of the directions in which the antennas are pointing. This type of interference can occur over substantial ranges. For example, with an 0.5 μs Ku band radar, aircraft similarly equipped within a radius of 97 nm could cause interference in clear weather. Since there could be up to 100 aircraft within this range of a busy airport, the potential interference could be serious. But it is interesting to note that under conditions when a landing monitor is really needed, i.e., 100 ft visibility fog, the range is very much reduced.

In 100 ft visibility fog, the interference is significant over a range of approximately 1 nm at V band, 5 nm at Ka band, 20 nm at Ku band, and 60 nm at X band.

o Methods for Overcoming Interference. - As regards the direct side-lobe to side-lobe interference, no alleviation is obtained from the low probability of the two antennas pointing at each other. The simplest way of reducing interference is to space the transmitter frequencies over a wide band. For example, if it were possible to utilize 50 separate channels, when there are 100 aircraft within interference range, an average of only two cause interference. In poor visibility, the number of radar equipped aircraft likely to be within interference range is assumed to be very much less than 100, and hence, the probability of interference becomes very small.

With main beam to side-lobe direct interference, any radar within optical range can, regardless of weather conditions, cause interference. Assuming there are 160 aircraft within this range; then, on average, antenna beam scanning reduces the number of radars producing interference signals at any one time to $160 \times \beta/\Phi$, where β is the azimuth beamwidth and Φ the sector scan angle. This number is 4 with a Ku-band radar. If the transmitter frequencies were spaced over a wide band, this type of interference would not be troublesome.

6.3.2 Passively-Cooperative Environment. - For identification of a runway with a mapping radar there must be a difference between the scattering coefficients of the runway and the adjacent ground. This is the case with airports having concrete runways surrounded by grass. However, when the airport is covered with snow, or when the ground between runways is paved with concrete or asphalt, there may be considerably less difference between the returns from the two areas; thus, the runway may be more difficult to see.

One method of overcoming this problem is to identify the runway with passive reflectors. Three ways of using these for IALM purposes are set out below:

1. A display showing reflectors and intercept point of flight vector. The pilot monitors the approach by noting the position of the flight vector intercept with respect to the touchdown reflector. A slight complication with this method can be experienced since the touchdown reflector has to be placed to one side of the runway thereby requiring use of an offset technique.

2. The radar is locked-on in azimuth and elevation planes to the touchdown reflector. From the angular information obtained the position of the aircraft relative to the glide path can be computed.

3. A track while scan radar is employed which tracks the touchdown reflector. This can provide, in addition to position relative to glide path, a high ground detection capability.

In this section we are mainly concerned with determining the optimum frequency band for the detection of reflectors. For this it is assumed that the following requirements must be met.

a) A number of reflectors might be placed so as to produce a pattern on the cockpit display which is immediately identifiable at a range of say 10 nm and indicates runway alignment and its threshold. A concept of this kind strongly suggests automated pattern recognition - an added degree of complexity.

b) The azimuth beamwidth of the radar must be small enough to prevent any large object or building on the airport being in the same pulse packet as the reflector.

c) For the required azimuth angular accuracy of 0.4°, the azimuth beamwidth should not exceed 2.0°. Alternatively, monopulse resolution enhancement may be employed in the horizontal plane and in this case the beamwidth need only be less than 10°.

d) The signal from a reflector should be 10 dB above noise.

e) The signal from a reflector should be 10 dB above the signal from terrain at the same range.

f) The signal from a reflector should be 10 dB above signal from rain at the same range.

Requirement (a) can be met with a variety of patterns. One suggestion is shown in Figure II-17, but the optimum pattern for a given airport will depend upon disposition of its buildings, aircraft parking areas, adjacent metropolitan features, etc. With a sufficient number of reflectors, it would, in theory, be possible to produce a coded pattern giving the identity of the airport. However, past experience (Ref.32) shows that confusion with returns from airport buildings makes runway identification difficult at a range of 10 nm.

Regarding Requirement (b), the X band radar with an azimuth beam width of 2.5° has a pulse packet width of 2,650 ft. at a range of 10 nm and, consequently, difficulty may be found in finding places for reflectors more than this distance from buildings. But with the higher frequency bands, this factor will be less of a problem because the width of the pulse packet will be correspondingly smaller.

To meet Requirement (c) with the X band radar, monopulse resolution improvement will have to be used in the azimuth plane. This will not be necessary on the other bands.

Requirements (d), (e) and (f) should be met with a reflector placed 1 nm beyond the threshold so that the line of the runway can be established. These requirements depend on equipment parameters and propagation conditions and will be considered separately for each frequency band.

The Ku, Ka, and V Band radars are postulated to be circularly polarized and the radar cross-section of a typical corner reflector will be below that obtained with linear polarization. However, this can be remedied by using the technique proposed by Latmiral and Sposito (Ref.33). These sources describe a method for improving the response of a corner reflector to a circularly polarized transmission by adding a wire grid to the reflector.

The individual elements of this combined analysis are contained in Section 6 of Volume III. In the following paragraphs, the results are reiterated and combined.

o X-Band Radar. - From Section 6 of Volume III, we obtain the following tables giving performance with a reflector having an echoing area of 1000 meters^2. This is produced with a corner reflector having a side dimension of 68 cms.

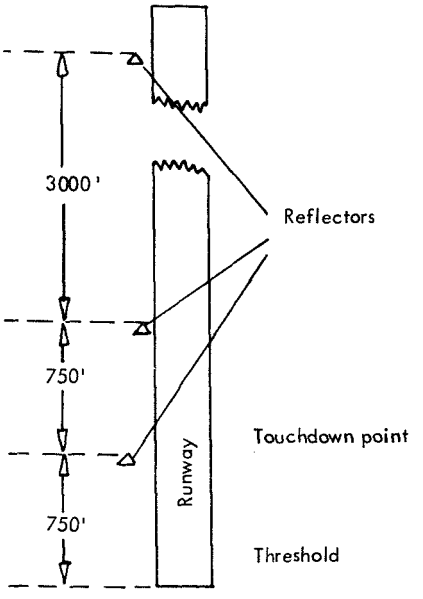

Figure II-17. Disposition of Reflectors

TABLE II-43. RANGE (nm)* AT WHICH THE REFLECTOR SIGNAL/NOISE RATIO HAS FALLEN TO 10 dB. ** --- Requirement (d)

Pulse Length	Rainfall Rates				Fog Densities	
μ sec	0 mm/hr	1 mm/hr	4 mm/hr	16 mm/hr	400 ft	100 ft
1.0	54 (100)	49 (90)	37 (68)	18 (34)	44 (82)	28 (52)
0.5	45 (84)	40 (74)	33 (61)	17 (32)	38 (70)	25 (47)
0.1	30 (56)	28 (51)	24 (44)	14 (26)	25 (47)	19 (36)

** Limiting Requirements are designated by lower case letters in each column.

* Ranges are given both in nm and km (kilometers in parentheses)

TABLE II-44. RANGE (nm)* AT WHICH THE REFLECTOR SIGNAL/TERRAIN SIGNAL RATIO HAS FALLEN TO 10 dB. ** --- Requirement (e)

Pulse Length (μs)	Range, nm (km) *
1.0	3.1 (5.7)
0.5	6.0 (11.0)
0.1	31.0 (57.0)

TABLE II-45. RANGE (nm)* AT WHICH THE REFLECTOR SIGNAL/RAIN ECHO RATIO HAS FALLEN TO 10 dB WITH LINEAR POLARIZATION --- ** Requirement (f)

Pulse Length μ sec.	Rainfall Rates		
	1 mm/hr	4 mm/hr	16 mm/hr
1.0	16 (30)	5.9 (11)	1.8 (3.4)
0.5	23 (43)	8.1 (15)	2.6 (4.8)
0.1	51 (95)	18 (34)	5.9 (11)

The three tables are combined to give the maximum range at which Requirements (d), (e) and (f) are all met. The Ranges are listed in Table II-46 together with the limiting requirement.

TABLE II-46. MAXIMUM RANGE (nm)* OF THE X-BAND RADAR ON A 1000 METER^2 REFLECTOR --- ** Limiting Requirement (see footnote)

Pulse Length μ sec	Rainfall Rates				Fog Densities	
	0 mm/hr	1 mm/hr	4 mm/hr	16 mm/hr	400 ft	100 ft
1.0	3.1(5.7)e	3.1(5.7)e	3.1(5.7)e	1.8(3.4)f	3.1(5.7)e	3.1(5.7)e
0.5	5.9(11)e	5.9(11)e	5.9(11)e	2.6(4.8)f	5.9(11)e	5.9(11)e
0.1	30 (56)d	28 (51)d	18.0(34)f	5.9(11)f	25 (47)d	19 (36)d

** Limiting Requirements are designated by lower case letters in each column.

* Ranges are given both in nm and km (kilometers in parentheses)

o Ku Band Radar. - Since a corner reflector with a side dimension of 68 cms is somewhat large, a smaller one, still giving an echoing area of 1000 meter^2, is considered for the Ku band radar. Such a reflector would have a side dimension of 54 cms. From Section 6, Vol. III, the ranges for Requirements (d), (e) and (f) are listed below.

TABLE II-47. RANGE (nm)* AT WHICH REFLECTOR SIGNAL/NOISE RATIO HAS FALLEN TO 10 dB. --- ** Requirement (d)

Pulse Length	Rainfall Rates				Fog Densities	
μ sec	0 mm/hr	1 mm/hr	4 mm/hr	16 mm/hr	400 ft	100 ft
1.0	65 (120)	38 (70)	22 (41)	7.6 (14)	34 (63)	18 (33)
0.5	54 (100)	34 (63)	21 (38)	7.0 (13)	31 (58)	17 (31)
0.1	36 (67)	27 (50)	17 (31)	6.5 (12)	24 (45)	14 (26)

TABLE II-48. RANGE (nm)* AT WHICH REFLECTOR SIGNAL/TERRAIN SIGNAL RATIO HAS FALLEN TO 10 dB. --- ** Requirement (e)

Pulse Length μ sec	Range, nm (km) *
1.0	5.0 (9.3)
0.5	10 (19)
0.1	50 (93)

** Limiting Requirements are designated by lower case letters in each column.

* Ranges are given both in nm and km (kilometers in parentheses)

TABLE II-49. RANGE (nm)* AT WHICH REFLECTOR SIGNAL/RAIN ECHO HAS FALLEN TO 10 dB WITH CIRCULAR POLARIZATION
--- ** Requirement (f)

Pulse Length μs	Rainfall Rates		
	1 mm/hr	4 mm/hr	16 mm/hr
1.0	46 (85)	16 (30)	6.5 (12)
0.5	65 (120)	23 (42)	9.2 (17)
0.1	143 (265)	51 (94)	20 (37)

From Tables II-47, 48 and 49, the maximum ranges which meet all the Requirements (d), (e) and (f), are obtained and these are listed in the Table II-50.

TABLE II-50. MAXIMUM RANGE (nm)* OF THE Ku BAND RADAR ON A 1000 METER^2 REFLECTOR. --- ** Limiting Requirement (see footnote)

Pulse Length μ sec	Rainfall Rates				Fog Densities	
	0 mm/hr	1 mm/hr	4 mm/hr	16 mm/hr	400 ft	100 ft
1.0	5.0(9.3)e	5.0(9.3)e	5.0(9.3)e	5.0(9.3)e	5.0(9.3)e	5.0(9.3)e
0.5	10 (19)e	10 (19)e	10 (19)e	7.0(13)d	10 (19)e	10 (19)e
0.1	36 (67)d	27 (50)d	17 (31)d	6.5(12)d	24 (45)d	14 (26)d

o Ka Band Radar. - At Ka band frequency, a corner reflector with an echoing area of 1000 meter^2 has a side dimension of 36 cm; the ranges at which the signal reflected from it meets Requirements (d), (e) and (f) are listed in the following tables. These tables have been derived from Section 6, Vol. III.

** Limiting Requirements are designated by lower case letters in each column.

* Ranges are given both in nm and km (kilometers in parentheses)

TABLE II-51. RANGE (nm)* AT WHICH REFLECTOR SIGNAL/NOISE RATIO HAS FALLEN TO 10 dB ** --- Requirement (d)

Pulse Length	Rainfall Rates				Fog Densities	
μ sec	0 mm/hr	1 mm/hr	4 mm/hr	16 mm/hr	400 ft	100 ft
1.0	54 (100)	17 (32)	8.1 (15)	3.2 (6)	19 (36)	7.0 (13)
0.5	45 (84)	16 (30)	7.6 (14)	3.1 (5.7)	17 (32)	6.5 (12)
0.1	30 (56)	12 (23)	6.5 (12)	2.8 (5.1)	14 (26)	5.4 (10)

TABLE II-52. RANGE (nm)* AT WHICH THE REFLECTOR SIGNAL/TERRAIN SIGNAL HAS FALLEN TO 10 dB ** --- Requirement (f)

Pulse Length μ sec	Range, nm (km) *
1.0	11 (20)
0.5	22 (40)
0.1	108 (200)

TABLE II-53. RANGE (nm)* AT WHICH THE REFLECTOR SIGNAL/RAIN ECHO HAS FALLEN TO 10 dB WITH CIRCULAR POLARIZATION ** --Requirement (f)

Pulse Length	Rainfall Rates		
μ s	1 mm/hr	4 mm/hr	16 mm/hr
1.0	19 (35)	7.6 (14)	3.3 (6.1)
0.5	26 (49)	10 (19)	4.6 (8.6)
0.1	59 (110)	23 (43)	10 (19)

* Ranges are given both in nm and km (kilometers in parentheses)

The maximum range at which Requirements (d), (e) and (f) are all met is listed in the following table.

TABLE II-54. MAXIMUM RANGE (nm) * OF THE Ka BAND RADAR ON A 1000 METER^2 REFLECTOR ** --- Limiting Requirement (see footnote)

Pulse Length	Rainfall Rates				Fog Densities	
μ sec.	0 mm/hr	1 mm/hr	4 mm/hr	16 mm/hr	400 ft	100 ft
1.0	11 (20) e	11 (20) e	7.6 (14) f	3.2 (6) d	11 (20) e	7.0 (13) d
0.5	22 (40) e	16 (30) d	7.6 (14) d	3.1 (5.7) d	17 (32) d	6.5 (12) d
0.1	30 (56) d	12 (23) d	6.5 (12) d	2.8 (5.1) d	14 (26) d	5.4 (10) d

o V Band Radar. - The performance of the V band radar on a 1000 meter^2 reflector is listed in the following tables. The corner reflector with this echoing area has a 26 cms side.

TABLE II-55. RANGE (nm)* AT WHICH THE REFLECTOR SIGNAL/NOISE HAS FALLEN TO 10 dB ** --- Requirement (d)

Pulse Length	Rainfall Rates				Fog Densities	
μ sec.	0 mm/hr	1 mm/hr	4 mm/hr	16 mm/hr	400 ft	100 ft
1.0	27 (50)	7.6 (14)	4.0 (7.4)	1.8 (3.4)	8.1 (15)	2.3 (4.3)
0.5	23 (43)	7.0 (13)	3.8 (7.0)	1.7 (3.2)	7.6 (14)	2.2 (4.1)
0.1	15 (28)	5.4 (10)	3.2 (5.9)	1.5 (2.8)	5.4 (10)	1.9 (3.5)

* Ranges are given both in nm and km (kilometers in parentheses)

** Limiting Requirements are designated by lower case letters in each column.

TABLE II-56. RANGE (nm)* AT WHICH THE REFLECTOR SIGNAL/TERRAIN SIGNAL HAS FALLEN TO 10 dB ** --- Requirement (e)

Pulse Length (μ sec)	Range, nm (km) *
1.0	22 (40)
0.5	43 (80)
0.1	216 (400)

TABLE II-57. RANGE (nm)* AT WHICH THE REFLECTOR SIGNAL/RAIN ECHO HAS FALLEN TO 10 dB WITH CIRCULAR POLARIZATION ** --- Requirement (f)

Pulse Length μs	Rainfall Rates		
	1 mm/hr	4 mm/hr	16 mm/hr
1.0	7.6 (14)	2.6 (4.9)	1.4 (2.5)
0.5	10 (19)	3.6 (6.7)	1.8 (3.4)
0.1	24 (44)	8.1 (15)	4.2 (7.8)

From Tables II-55, 56 and 57, the following table is obtained which lists the maximum range that at which Requirements (d), (e) and (f) are all met.

* Ranges are given both in nm and km (kilometers in parentheses)

TABLE II-58. MAXIMUM RANGE (nm)* OF THE V-BAND RADAR ON A 1000 METER^2 REFLECTOR ** --- Limiting Requirement (see footnote)

Pulse Length	Rainfall Rates				Fog Densities	
μ sec.	0 mm/hr	1 mm/hr	4 mm/hr	16 mm/hr	400 ft	100 ft
1.0	22 (40)e	7.6 (14)f	2.6 (4.9) f	1.4 (2.5) f	8.1 (15) d	2.3 (4.3) d
0.5	23 (43)d	7.0 (13)d	3.6 (6.7) f	1.7 (3.2) d	7.6 (14) d	2.2 (4.1) d
0.1	15 (28)d	5.4 (10)d	3.2 (5.9)d	1.5 (2.8) d	5.4 (10) d	1.9 (3.5) d

* Ranges are given both in nm and km (kilometers in parentheses)
** Limiting Requirements are designated by lower case letters in each column.

(B) Interference. - With runway reflectors, the background interference from other aircraft is not so pronounced as it is with with unenhanced runways. This is because the interference signal has to be greater than the reflector signal instead of the terrain signal, and the system is designed so that the reflector signal is always more than 10 dB above the terrain signal.

Section 6.3.1.B shows that with unenhanced runways interference signals will appear on the PPI but the amount should not be too troublesome. Hence, with runway reflectors interference should not be a "problem".

Optimum Frequency Band for the Detection of Runway With Passive Reflector Enhancement. - Table II-59 lists the ranges at which a 1000 m^2 reflector is detected in 100-ft visibility fog, with radars operating on different frequency bands employing antennas with horizontal apertures of 0.5 m, 1.0 m and 1.5 m. Ranges are given for transmitter pulse lengths of 1.0, 0.5 and 0.1 μsec.

This Table shows that the detection range falls with a decrease in the size of the horizontal aperture of the antenna but, even with a 0.5 m antenna (aperture), adequate ranges can be obtained with the X- and Ku-band radars.

In summary, it has been shown that the best performance with a reflector having the smallest mechanical dimensions is obtained with the Ku band radar. A Ku band radar having a 0.1 μsec pulse and a nominal 1 m antenna requires a corner reflector with a side dimension of 37.5 cms in order to achieve a detection range of 10 nm in 100 ft visibility fog. Installation conditions might either dictate a smaller antenna or allow a larger antenna. Using the same reflector, reducing the antenna size from 1 m to 0.5 m reduces the range from 10 nm to 7 nm On the other hand, increasing the antenna size from 1 m to 1.5 m increases the detection range from 10 nm to 12 nm.

The following subparagraphs, including Tables II-60, 61 and 62 contain a discussion showing how these results were obtained.

The detection range of reflectors having a radar cross-section of 1000 m^2 is shown in Table II-60 . Which is the optimum frequency is not immediately obvious from the Table, since the choice depends upon a determination as to which operational feature is considered most important.

V-band would probably be ruled out because of its inherently poor performance in rain and in 100 ft. visibility fog. It has, however, excellent performance in clear weather and offers quite reasonable performance in 400 ft. visibility fog.

The X-band radar with a narrow transmitter pulse gives excellent performance in most weather conditions, including rainfall rates of up to 16 mm/hr. However, if there is a requirement for the display to be supplemented with a radar map of the runway, the wide beamwidth at X band precludes this frequency.

Both the Ku and Ka-band radars provide good performance in all weather conditions except very heavy rainfall; the ranges offered at Ku band are somewhat greater than at Ka band because of the lower attenuation experienced in rain and fog.

TABLE II-59. DETECTION RANGE (nm)* IN 100-ft FOG OF 1000 m^2 REFLECTOR WITH ANTENNAS OF VARIOUS HORIZONTAL SIZES

Frequency Band	Pulse Length (μs)	Antenna Horizontal Aperture (m)		
		0.5 m	1.0 m	1.5 m
X	1.0	1.5 (2.8)	3.1 (5.7)	4.7 (8.7)
	0.5	3.0 (5.6)	5.9 (11)	9.0 (16.7)
	0.1	15.0 (27.8)	19 (36)	22.0 (40.8)
Ku	1.0	2.5 (4.6)	5.0 (9.3)	7.5 (13.9)
	0.5	5.0 (9.3)	10 (19)	15.0 (27.8)
	0.1	10.0 (18.5)	14 (26)	17.0 (31.5)
Ka	1.0	4.9 (9.1)	7.0 (13)	9.1 (16.9)
	0.5	4.5 (8.3)	6.5 (12)	8.2 (15.2)
	0.1	3.8 (7.0)	5.4 (10)	6.7 (12.4)
V	1.0	1.6 (3.0)	2.3 (4.3)	2.9 (5.4)
	0.5	1.5 (2.8)	2.2 (4.1)	2.7 (5.0)
	0.1	1.3 (2.4)	1.9 (3.5)	2.4 (4.4)

* Ranges are given both in nm and km (kilometers in parentheses)

Table II-60 shows that a reflector cross-section of 1000 m^2 is unnecessarily large, especially at the lower frequencies, because for the most part the range capability exceeds the required 10 nm. A corner reflector only displays a correct cross section over a particular range of incidence angles . .. that is when the reflecting surfaces are at the correct angle to one another within a close tolerance. The larger the cross section, the closer is the required tolerance. It will be difficult to achieve this with 1000 meter^2 reflectors; hence, it is very desirable to reduce the reflector size.

The minimum reflector cross section for a given range is obtained when the pulse length is such that the Reflector Signal/Noise and Reflector Signal/Terrain Signal are both equal to 10 dB at the stated range. Values for the cross section and pulse length that meet this requirement have been presented in Section 6 of Volume III, and from these data Table II-61 has been derived for 100-ft visibility fog, the most stringent of the meteorological design criteria.

TABLE II-60. RANGE (nm) AT WHICH A 1000 m^2 REFLECTOR IS DETECTED

(a) Under Nominal Rainfall Rates

Pulse Width μs	Rainfall Rates			
	0 mm/hr	1 mm/hr	4 mm/hr	16 mm/hr
1.0	3.1 5 11 22	3.1 5 11 7.6	3.1 5 7.6 2.6	1.8 5 3.2 1.4
0.5	5.9 10 22 23	5.9 10 16 7.0	5.9 10 7.6 3.6	2.6 7 3.1 1.7
0.1	30 36 30 15	28 27 12 5.4	18 17 6.5 3.2	5.9 6.5 2.8 1.5
	X Ku Ka V	X Ku Ka V	X Ku Ka V	X Ku Ka V
		FREQUENCY BAND		

(b) Under the two Selected Fog Density Conditions

Pulse Width μs	Fog Densities	
	400 ft	100 ft
1.0	3.1 5.0 11 8.1	3.1 5.0 7.0 2.3
0.5	5.9 10 17 7.6	5.9 10 6.5 2.2
0.1	25 24 14 5.4	19 14 5.4 1.9
	X Ku Ka V	X Ku Ka V
	FREQUENCY BAND	

TABLE II-61. OPTIMUM CORNER REFLECTOR SIZE AND TRANSMITTER PULSE LENGTH FOR VARIOUS DETECTION RANGES IN 100 ft FOG

Frequency Band	Maximum Detection Range, nm * →	10	5	2
X	Reflector Cross Section, m^2	130	19	1.6
	Reflector Side Dimension, cm	51	25	13.5
	Pulse Length, μs	0.04	0.01	0.002
Ku	Reflector Cross Section, m^2	220	17	1.0
	Reflector Side Dimension, cm	37.5	20	1.2
	Pulse Length, μs	0.10	0.015	0.002
Ka	Reflector Cross Section, m^2	2500	220	2.6
	Reflector Side Dimension, cm	46	25.5	8.3
	Pulse Length, μs	2.5	0.35	0.013
V	Reflector Cross Section, m^2	2×10^{12}	2.7×10^{6}	220
	Reflector Side Dimension, cm	—	—	17.7
	Pulse Length, μs	4×10^{9}	9.3×10^{3}	2.2

The 'theoretical' attenuation for fog has been assumed in this table; if this value is halved -- to give an indication of probable performance in practice -- the values for Ka and V bands change to those listed in Table II-62. The performance at X and Ku bands is only slightly affected.

Tables II-61 and II-62 show that for a maximum range requirement of 10 nm, either X or Ku band radars should be used. If the attenuation in fog is less than the theoretical value, it would be possible to use a radar operating on Ka band. With V band, the maximum practical detection range in 100-ft visibility fog is only about 3 nm, and this is achieved only when the attenuation is half the theoretical value.

TABLE II-62. OPTIMUM CORNER REFLECTOR SIZE AND TRANSMITTER PULSE LENGTH FOR VARIOUS DETECTION RANGES IN 100 ft FOG -- HALF THEORETICAL ATTENUATION

Frequency Band	Maximum Detection Range, nm * →	10	5	2
Ka	Reflector Cross Section, m^2	1000	46	1.4
	Reflector Side Dimension, cm	37	17.2	7.2
	Pulse Length, μs	1.0	0.07	0.007
V	Reflector Cross Section, m^2	very	very	21
	Reflector Side Dimension, cm	large	large	10.2
	Pulse Length, μs	values	values	0.2

In most cases the transmitter pulse length best suited for minimum sized reflectors is less than 0.1 μs. Such a transmitter would occupy a wide frequency spectrum which would increase the potential amount of interference. It is, therefore, desirable to increase the pulse length to at least 0.1 μs in order to keep the interference down to a reasonable level. However, it is also desirable to keep the pulse length at 0.1 μs to allow a minimum range of 100 ft. When the pulse length is increased from its optimum value there must be a corresponding increase in the reflector cross section in order to maintain the reflector Signal/Terrain Signal at 10 dB at maximum range. The resulting reflector size is given in Table II-63.

Table II-63 shows that the frequency band which requires the smallest reflector kit is Ku band; to meet a range requirement of 10 nm, reflector size should be 220 $meters^2$. With this reflector, the rainfall rate will have to exceed 16 mm/hr before rain-front echoes become a nuisance.

TABLE II-63. REFLECTOR SIZE FOR VARIOUS DETECTION RANGES IN 100 ft FOG. FIGURES IN PARENTHESES GIVE TYPICAL PERFORMANCE ASSUMING HALF THEORETICAL ATTENUATION

Frequency Band	Maximum Detection Range, nm →	10	5	2
X	Reflector Cross Section, m^2	325	170	70
	Reflector Side Dimension, cm	51	43	35
	Pulse Length, μs	0.1	0.1	0.1
Ku	Reflector Cross Section, m^2	220	114	42
	Reflector Side Dimension, cm	37.5	31.6	24.6
	Pulse Length, μs	0.1	0.1	0.1
Ka	Reflector Cross Section, m^2	2500 (1000)	220 (65)	18.8 (21)
	Reflector Side Dimension, cm	46 (37)	25.5 (18.6)	13.7 (14.7)
	Pulse Length, μs	2.5 (1.0)	0.35 (0.1)	0.1 (0.1)
V	Reflector Cross Section, m^2	very	very	(21)
	Reflector Side Dimension, cm	large	large	(10.2)
	Pulse Length, μs	values	values	(0.2)

o Pattern Recognition. - Modern airports with large clusters of buildings can produce a complex radar map which can cause the pilot difficulty in identifying the reflector pattern at a 10 nm range. It is conceivable that a system could, be developed which would automatically identify a given pattern of radar returns; however, this kind of capability suggests a degree of system complexity which is undesirable. A much simpler solution involves the use of two or more reflectors, spaced given distances apart in a direction parallel to the runway, to give a signal comprising a number of pulses separated by known intervals. By processing the video output of the radar with circuits using delay lines, it is possible to eliminate all signals unless they have this precise coding. By installing along the runway a number of these space coded reflectors it should, in theory, be possible to show the runway without extraneous signals. In practice, however, the cancellation will not be perfect and experimental work should be carried out to establish the improvement that can be gained with this approach.

6.3.3 Actively-Cooperative Environment. -

o Beacon Transponders. - The disadvantage of a landing monitor which has to operate without any radar enhancement on the ground is that at long ranges, and particularly when the ground is covered with snow, it may be difficult if not impossible to detect the runway. Passive reflectors along the runway could provide a simple solution to the problem and, with the techniques suggested above could significantly reduce the number of the potentially confusing returns from airport buildings.

Alternatively, beacons could be used in place of reflectors to identify the runway. These could be coded to give positive identification and thus would aid the pilot in identifying airport, runway complex and in the presence of parallel runways, the correct one. They would enable the pilot to be absolutely sure that he is monitoring approach to the correct point on the runway of intended landing.

It could be argued that the beacon system would not be so reliable as one using passive reflectors. But with modern solid state techniques, together with employment of redundant configurations, it should be possible to satisfy the most stringent requirements in this respect.

In order to minimize unnecessary triggering of the beacons, they would be fitted with directive antennas so that only aircraft flying the approach path would operate them.

o Possible Beacon Systems. - A beacon may reply either on the same frequency as the transmitter or on a different frequency. When the beacon's frequency differs from that of the radar, the display in the aircraft can be designed to display only the beacon's response. The energy returned from terrain, runways and airport buildings is at the radar frequency and, therefore, can be rejected. Runway identification is significantly simpler once the entire background of radar information is removed from the display. A further advantage of this method is the fact that the beacon has only to produce a signal which is substantially above the receiver noise, rather than a signal which is substantially above the terrain return. This means that a lower level of beacon power is required.

As with corner reflectors, adequate azimuth angular accuracy can be obtained without monopulse resolution enhancement, except at X band.

Section 6, Vol. III presents the results of calculations of the power required to produce a Beacon Signal/Noise Ratio of 10dB at a range of 10 nm. The power required when in the presence of 100 ft. visibility fog or 16 mm/hr rain is listed in the following table. The beacon antenna is assumed to have azimuth and elevation beamwidths of 10°.

TABLE II-64. BEACON POWER REQUIRED

Frequency Band	Pulse Length (μs)	Beacon Power Requirements (mW)	
		100 ft Visibility Fog	16 mm/hr Rain
X	1.0	0.044	0.09
	0.5	0.088	0.18
	0.1	0.44	0.90
Ku	1.0	0.19	8.1
	0.5	0.38	16.2
	0.1	1.90	81
Ka	1.0	84	6.6×10^6
	0.5	168	13.2×10^6
	0.1	840	6.6×10^7
V	1.0	5×10^{10}	1.2×10^{13}
	0.5	1×10^{11}	2.4×10^{13}
	0.1	5×10^{11}	1.2×10^{14}

This table shows that a V band beacon requires a very large transmitter power, thus, would not be practical. The Ka band system would require reasonable power for operation in 100 ft. visibility fog but would be excessive for operation in 16 mm/hr rainfall. Both Ku and X band systems are seen to operate satisfactorily with transmitter power that can be achieved with solid state sources (Ref. 34), even when there is severe attenuation in the 16 mm/hr rain. It should be noted that no echoes are received from rain with a beacon system.

Reducing the pulse length of the airborne system improves accuracy in range and since the beacon power required with a 0.1 μs pulse system is easily achieved, it is recommended that this value be specified in design of an IALM which is to incorporate a beacon.

To show the line of the runway as well as the touchdown point, at least two beacons are required. By arranging for the beacons to give a coded reply consisting of a number of pulses at specific spacing, both the threshold and identity of the runway can be established.

o Interference. - Since the beacon will respond to any input signal above a given strength and at the right frequency, the presence of a large number of aircraft near an airport could cause confusion as to the correct location of the threshold. In addition to the wanted signal, there could be a multiplicity of extraneous replies appearing on the cockpit display. On a visual display, these extraneous replies would appear to be random in nature and would not be mistaken for false replies. With suitable precautions they can be reduced to an acceptable level.

The beacon antenna should be directed so that only aircraft within a specified bearing of the approach path could trigger the beacon. In the azimuth direction, the beamwidth should be wide enough so that an aircraft positioned 10nm from the runway, with a typical navigation error, is still within it. For example, if this error were 1nm in a cross-track direction, the beamwidth would have to be 12°. In the elevation direction, the beamwidth should be wide enough to cater to all possible approach angles in the order of 1° to 10°.

Interference will occur only when two aircraft transmitting antennas point simultaneously at a beacon. As shown in Section 6.3.1.B, the probability of this happening is 1 in 1600 with the Ku-band radar. Thus, if there are 50 aircraft in the beacon beam, the probability of interference would be 1 in 32. This level of interference is probably acceptable. But if flight trials show that this is not the case, interference suppression techniques would have to be used in radar receiver.

As the aircraft approaches the beacon, the amplitude of the signal received from the side lobes of the radar's antenna enentually becomes strong enough to trigger the beacon. For example, with a side lobe level of -30dB, a beacon which is just triggered by the main beam at a range of 10nm is triggered by the side lobes at a range of 1900 ft. When this occurs, the extra beacon pulses transmitted will increase the interference level. Side lobe triggering can be prevented by arranging for the beacon assumed to be located at the side of runway at the touchdown point, to have an azimuth polar diagram shaped, so that at short ranges, the radar side lobe signal received by the beacon is reduced below triggering level.

Referring to Figure II-18, the signal received by the beacon is proportional to

$$\frac{f(\theta)}{R^2} = \frac{f(\theta)\sin^2\theta}{d^2}$$

where $f(\theta)$ = antenna gain in direction θ, R = range and d = beam offset.

Hence, if $f(\theta)$ is made proportional to $\text{cosec}^2\theta$, the signal received by the beacon is kept constant as the range decreases. Although it is impracticable to make the polar diagram follow this for values of θ up to 90°, it is possible to reduce the amount of side lobe triggering to an insignificant level.

o Optimum Frequency Band for Beacon System. - With both Ka and V frequency bands the beacon transmitter power required is very large and it is well outside the range of present day solid state techniques. The disadvantage of X band is that monopulse would have to be provided in the azimuth plane in order to achieve adequate accuracy. Hence, it is concluded that the optimum frequency band is Ku.

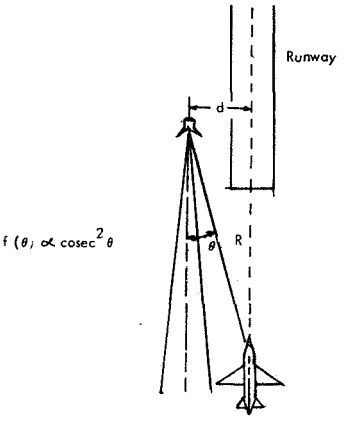

Figure II-18. Beacon Antenna Polar Diagram for Reducing Side-Lobe Triggering

6.4 Detection and Identification of High Ground Hazards to Flight - The Terrain Avoidance Problem

6.4.1 Introduction. - Errors in navigation have resulted in numerous aircraft flying into high ground both enroute and during the approach phase. Accidents of this type can be prevented by fitting the aircraft with a radar which detects high ground in and near the flight path of the vehicle and which warns the pilot that he should maneuver the aircraft to prevent a collision. In order not to subject the aircraft and its passengers to undue stress, the high ground should be detected in sufficient time for only a gentle avoidance maneuver to be necessary and, as shown in Section 4 of this Volume, this is of the order of 5 nm. The information presented to the pilot should enable him to decide whether to climb or to turn in order to prevent a collision.

An essential feature of any high ground avoidance radar is that false alarms should be reduced to a very low level. These may arise from receiver noise, interference from other radars and from rain echoes. An equipment that gave an unnecessary warning once or twice per flight would not be acceptable.

In its simplest form the radar determines range to ground along a path fixed in azimuth and depressed 1° to 2° below the flight vector. The systems would produce a warning when the range is less than 5 nm. The disadvantage of such a system is that it could be dangerous for the pilot to turn since there is no information about the terrain on either side of the flight vector. Consequently, it is proposed that the radar scans in azimuth and obtains information on the height of the terrain in a sector of $\pm 30^\circ$ about headings. This would be shown on a display and, in addition, it can be arranged for the presence of ground within certain range and clearance height limits to give both an aural and a visual warning signal.

In military terrain avoidance systems, it is usual to show on a PPI, ground which appears above an assumed horizontal plane defined at a predetermined distance below the aircraft... as set by a range-gating type device. Area of ground coverage is limited to a range extending from approximately 1/2 mi. to 10 nmi (or more) in front of the aircraft. This requires a wide elevation beamwidth. However, for civil applications, the radar may have to provide, in addition, a landing monitor facility which would require that the elevation beamwidth be relatively small if the radar is to give satsifactory performance in this mode. Since civil aircraft require a warning system rather than one which allows continuous terrain avoidance to be carried out, the narrower beamwidth would be adequate.

Normally in a monopulse system, terrain above a plane containing the antenna boresight line is displayed. But with off-boresight processing (Ref. 24), it is possible to display terrain that extends above a horizontal plane that can be positioned a preset distance below the aircraft. The extent of this clearance plane is determined by the elevation beamwidth. Figure II-19(a) shows the minimum detection ranges of the radars having the elevation beamwidths given in Table II-26 for clearance heights of 1000 ft. and 2000 ft. Any ground above the clearance plane would be shown on a display and, in addition, any high ground along the flight path of the aircraft would operate a warning signal. Although the clearance plane does not extend to a minimum range of 1/2 nm, it would appear to be impossible for a civil aircraft to maneuver in such a manner that high ground, not first detected in the range of 2 to 5nm, could hazard the aircraft. The clearance height finally chosen would depend upon experience gained during flight testing, but will probably be between 1000 and 2000 ft.

During the landing phase, it can be argued that when the runway threshold is seen on the display and is properly intercepted by the radar boresight axis, it is impossible for any high ground to be in the path of the aircraft.

It is, therefore, not essential to provide an extensive ground avoidance capability. However, as discussed in Section 4 of this Volume, high ground along the approach path that is likely to hazard the aircraft should be detected and a warning given to the pilot. The technique used enroute for detecting ground above a fixed horizontal clearance plane cannot be used when the aircraft is on the approach path since the touchdown point will eventually appear above it. Consequently, the clearance plane must be shaped as shown, for example, in Figure II-20 and this must be continually changed as the range decreases in order to prevent unnecessary high ground warnings.

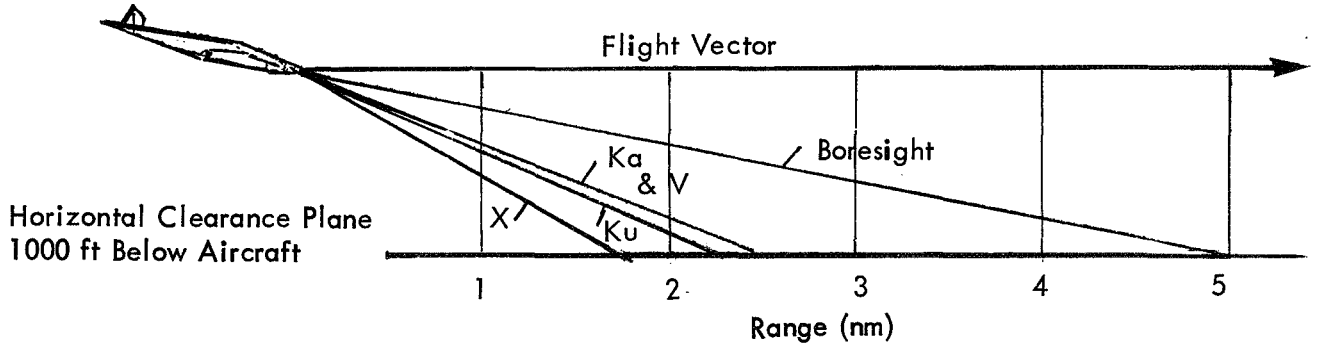

Figure II-19(a) Extent of Clearance Plane

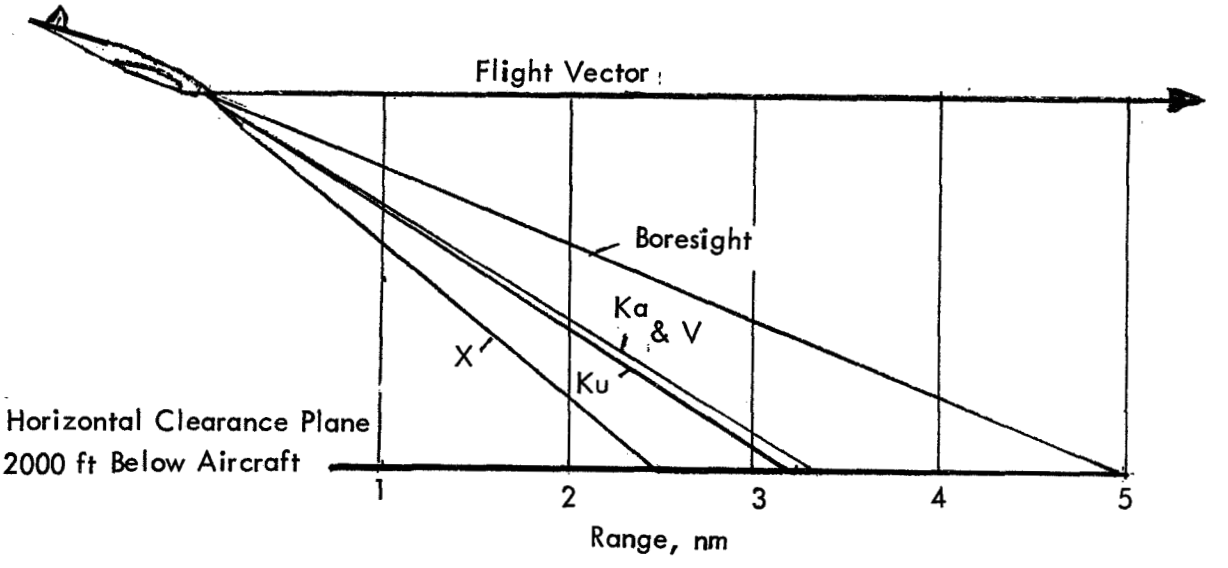

Figure II-19 (b). Extent of Clearance Plane

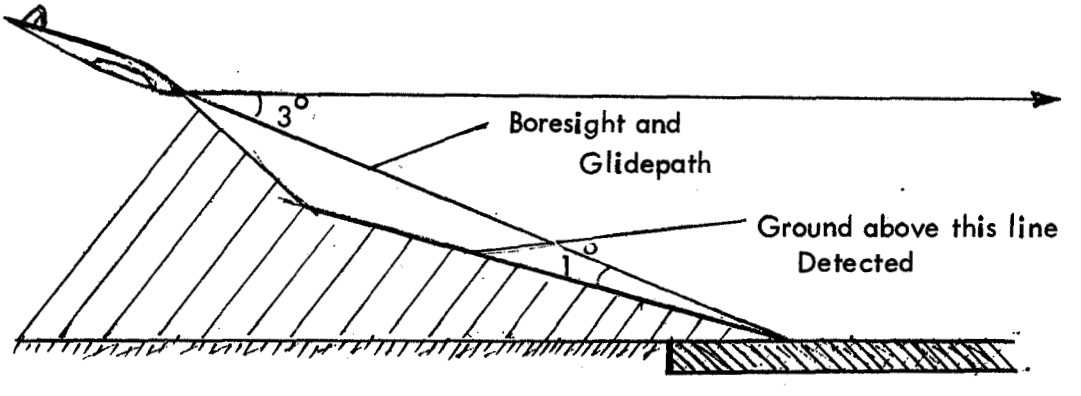

Figure II-20. High Ground Detection in Landing Phase

6.4.2 Accuracy Requirements.- For high ground avoidance, the critical radar parameter is the boresight accuracy in the elevation plane. It is this parameter which determines the minimum clearance height that can be selected. This clearance height must be larger than the height error due to uncertainty in the boresight position. With a monopulse system, the boresight angular error is, typically, elevation beamwidth divided by 20 (Ref.25). For example, with the Ku band radar, it is $4.5/20 = 0.23^{\circ}$. This is well below the 0.6° given in Section 4.5.2 of this Volume for the overall elevation angle error.

The boresight depression angle depends upon the clearance height and warning range required. For example, if these are 100 ft. and 5 nm, respectively the angle is 2°. The boresight should be depressed 2° from the flight vector. This requires knowledge of aircraft angle of attack. This quantity can be obtained from an Airstream Detection Device. Alternatively, the boresight could be depressed from the horizontal by the selected angle in deference to the argument that during straight and level enroute flying the flight vector is always horizontal. During the descent phase the angle would be increased so as to maintain the the selected angle below the flight path.

6.4.3. Signal Level Requirements. - The equipment should be set up so that any signal at less than the maximum detection range, which has a sum component above a given threshold and a difference component above a given angle with respect to the boresight, is recognized as high ground and is shown on a display. A critical design feature is the threshold level. If it is too low, false signals are produced from noise and from rain fronts. Though uniform area of rainfall will not produce an above-boresight signal with a monopulse radar, a rain front with a suitable slope could produce a signal denoting high ground. On the other hand, if the threshold level is set too high, high ground may not be detected. Therefore, the threshold setting is selected as a careful compromise and, as shown below, varies with range in order to obtain the best performance.

Referring to Figure II-21, the threshold level is arbitrarily set 20dB above receiver noise level to prevent random noise spikes from appearing as signals. In order to prevent rain echoes producing false signals the threshold level is raised as the range decreases. But to ensure that high ground is always detected the threshold level at which a signal will be displayed is set 6dB below the calculated signal level for terrain with presence of 16 mm/hr rainfall between the aircraft and the high ground. This caters to the maximum path attenuation and allows for 6dB fall-off in radar performance. A rain echo has to be above this level to produce a false signal. In summary the equipment should meet the following:

Requirements:

(a) Returns from terrain within 10nm of the aircraft must produce a signal which is more than 20dB above the receiver noise level even in the presence of rainfall rates of 16mm/hr.

(b) Triggering threshold level should be set at 6dB below the expected signal level of the return from terrain.

(c) The sum signal from a rain-front must not exceed threshold level.

It should be noted that Requirements (a) and (b) must be met to detect a hazardous situation. Requirement (c) should be met to prevent false warnings.

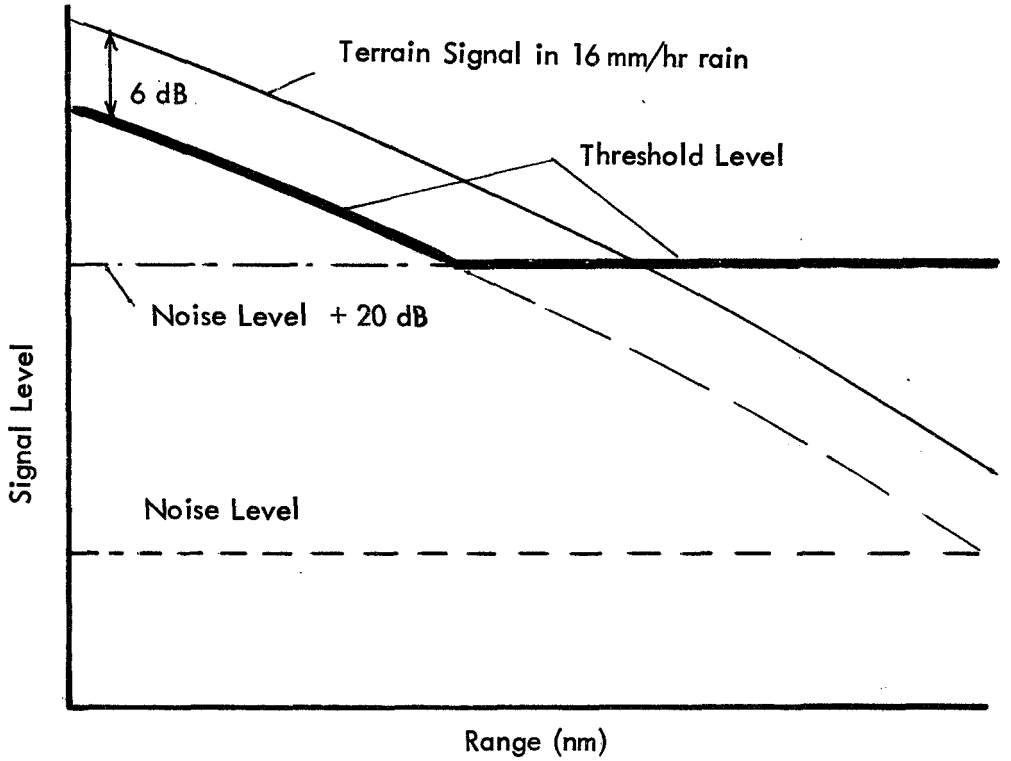

Figure II-21. Threshold Level

o X-Band Radar. - The ranges at which Requirement (a) is met in various weather conditions are listed in Table II-65. These have been derived from Table III-14 of Volume III

TABLE II-65. RANGE (nm)* AT WHICH TERRAIN SIGNAL/NOISE IS 20 dB WITH THE X-BAND RADAR (RANGE IN km IN PARENTHESES)

Pulse Length	Rainfall Rates				Fog Densities	
μ sec.	0 mm/hr	1 mm/hr	4 mm/hr	16 mm/hr	400 ft	100 ft
1.0	30.0 (55.0)	28.0 (52.0)	22.0 (41.0)	12.0 (22.0)	26.0 (48.0)	18.0 (33.0)
0.5	19.0 (35.0)	18.0 (33.0)	15.0 (28.0)	8.6 (16.0)	17.0 (31.0)	13.0 (24.0)
0.1	6.5 (12.0)	6.5 (12.0)	5.9 (11.0)	4.3 (8.0)	5.9 (11.0)	5.4 (10.0)

* Ranges are given both in nm and km (kilometers in parentheses)

The threshold level is derived from Table III-28 of Volume III by subtracting 6dB from the terrain signal when the rainfall density is 16 mm/hr, provided this does not fall below a level corresponding to receiver noise plus 20dB. The values obtained are given in the following table for pulse lengths of 1.0, 0.5 and 0.1 μs.

TABLE II-66. THRESHOLD LEVEL (-dBW) FOR X-BAND RADAR

Range * nm (km)	Pulse Length		
	1.0 μs	0.5 μs	0.1 μs
0.54 (1)	68.22	71.22	78.22
1.08 (2)	77.74	80.74	87.74
2.16 (4)	87.78	90.78	97.78
5.40 (10)	102.90	105.90	104.00
10.8 (20)	114.00	111.00	104.00

* Ranges are given both in nm and km (kilometers in parentheses)

From Equation (32) of Section 6, Volume III, the following table has been obtained which lists the rain-front signals at various ranges. The attenuation between the aircraft and the rain-front is assumed to be zero.

TABLE II-67. RAIN-FRONT SIGNALS (-dBW) AT X BAND

Range nm (km)	Pulse Length								
	1 mm/hr rain-front			4 mm/hr rain-front			16 mm/hr rain-front		
	1.0 μs	0.5 μs	0.1 μs	1.0 μs	0.5 μs	0.1 μs	1.0 μs	0.5 μs	0.1 μs
0.54 (1)	83.7	86.7	93.7	74.7	77.7	84.7	64.7	67.7	74.7
1.08 (2)	89.7	92.7	99.7	80.7	83.7	90.7	70.7	73.7	80.7
2.16 (4)	95.7	98.7	105.7	86.7	89.7	96.7	76.7	79.7	86.7
5.40 (10)	103.7	106.7	113.7	94.7	97.7	104.7	84.7	87.7	94.7
10.8 (20)	109.7	112.7	119.7	100.7	103.7	110.7	90.7	93.7	100.7

The threshold level is indicated by the thick line in this table. At ranges below the line the rain echoes are above the threshold and therefore will appear on the radar display.

The relation of the rain echo signal to the threshold level is also shown in Figure II-22 for a pulse length of 1.0 μs. This shows that a 1 mm/hr rain echo is above the threshold at 6.5 nm and at 1.5 nm from 4 mm/hr rain. With 16 mm/hr rain the echo is above the threshold at all ranges.

It is known from in-service experience with X band terrain following radars that the rain echoes have much less effect on performance than that which is predicted above. This is almost certainly due to the following three causes. First, with high ground the angle of grazing is, in general, much greater than the 3° assumed to cover the landing approach phase - an angle of 30° might be more typical value the result of which would be an increase in the estimated terrain signal of 10dB. Second, the radar cross section of rain is likely to be 10dB below the theoretical value. Thirdly, the water content of clouds

TABLE II-68. TYPICAL HGA PERFORMANCE OF THE X-BAND RADAR WITH A (1.0 μs) PULSE LENGTH

Range of high ground detection through 1 g/m^3 cloud, or fog	* 38 (70.4)
Range of high ground detection through 16 mm/hr rain	16 (29.6)
Range at which a 16 mm/hr rain echo exceeds threshold level	8 (14.8)

* Ranges are given both in nm and km (kilometers in parentheses)

covering the high ground is not likely to exceed 1 gram/meter^3, which is about that assumed for fog of 100 ft visibility -- this halves the attenuation since this is directly proportional to water content.

With these 'typical' values, the performance obtained is given in Table II-68. These have been derived by making the appropriate substitutions in the equations given in Section 6, Volume III.

No assessment has been made of the 'typical' performance for pulse lengths of 0.5 and 0.1 μs since Table II-65 shows that it would be inferior to that obtained with 1μs.

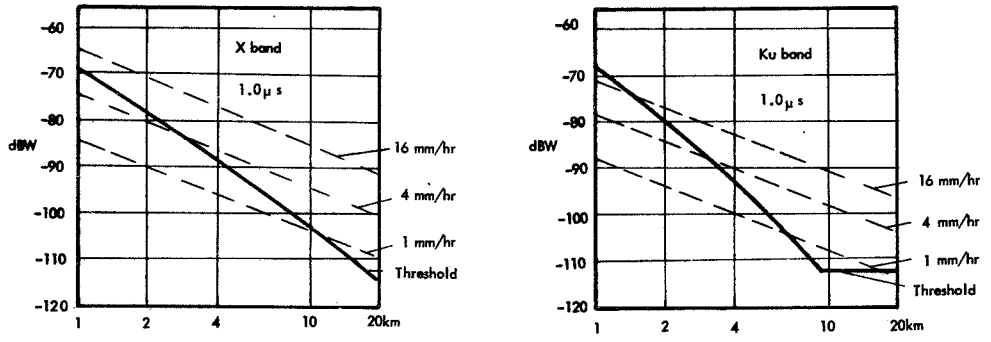

Figure II-22. Amplitude of Rain Echoes -- X and Ku Bands

o Ku Band Radar. - The performance of the Ku-band radar, derived in a manner similar to that of the X-band radar, is summarized in the following tables.

TABLE II-69. RANGE (nm)* AT WHICH TERRAIN SIGNAL/NOISE IS GREATER THAN 20 dB WITH Ku BAND

Pulse Length	Rainfall Rates				Fog Densities	
μ sec	0 mm/hr	1 mm/hr	4 mm/hr	16 mm/hr	400 ft	100 ft
1.0	32 (60)	22 (41)	13 (24)	5.1(9.5)	20.5(38)	11 (20)
0.5	19 (35)	15 (27)	9.2(17)	3.9(7.2)	14 (25)	7.6(14)
0.1	6.5(12)	5.9(11)	4.5(8.4)	2.4(4.5)	5.4(10)	3.8(7.1)

* Ranges are given both in nm and km (kilometers in parentheses)

With a 1.0 μs equipment the range is greater than 10nm, except when rainfall of 16 mm/hr extends between the aircraft and the terrain; in that case the range falls to 5.1 nm.

From Equations (22) and (28) of Section 6, Volume III, the following table has been derived listing the threshold level which meets Requirement (b) for transmitter pulse lengths of 1.0, 0.5 and 0.1 μs.

TABLE II-70. THRESHOLD LEVEL (-dBW) AT Ku BAND

Range km (nm) *	Pulse Length		
	1.0 μs	0.5 μs	0.1 μs
1 (0.54)	67.26	70.26	77.26
2 (1.08)	78.82	81.82	88.82
4 (2.16)	93.94	96.94	102
10 (5.39)	112	109	102
20 (10.78)	112	109	102

The amplitude of the rain-front signal derived from Equation (33) of Section 6, Vol. III is listed below for various pulse lengths. Circular polarization is assumed.

TABLE II-71. RAIN-FRONT SIGNALS (-dBW) AT Ku BAND

Range km (nm) *	Rainfall Rates								
	1 mm/hr rain-front			4 mm/hr rain-front			16 mm/hr rain-front		
	1.0 μs	0.5 μs	0.1 μs	1.0 μs	0.5 μs	0.1 μs	1.0 μs	0.5 μs	0.1 μs
1 (0.54)	87.6	90.6	97.6	78.6	81.6	88.6	70.6	73.6	80.6
2 (1.08)	93.6	96.6	103.6	84.6	87.6	94.6	76.6	79.6	86.6
4 (2.16)	99.6	102.6	109.6	90.6	93.6	100.6	82.6	85.6	92.6
10 (5.39)	107.6	110.6	117.6	98.6	111.6	108.6	90.6	93.6	100.6
20 (10.78)	113.6	116.6	123.6	104.6	107.6	114.6	96.6	99.6	106.6

At ranges below the thick line the rain echo is above the threshold level. A more exact indication of the range beyond which the echo exceeds the threshold is obtained from Figure II-22 for a pulse length of 1.0μs. This shows that ranges are as follows:

1 mm/hr - 3.8 nm

4 mm/hr - 1.6 nm

16 mm/hr - 0.8 nm

When the range calculations are based on 'typical' conditions, the following performance is obtained.

TABLE II-72. TYPICAL HGA PERFORMANCE OF THE Ku BAND RADAR WITH A (1.0 μs) PULSE LENGTH

Range of high ground detection through 1 g/m^3 cloud, or fog	22.0 nm	(40.8) km
Range of high ground detection through 16 mm/hr rain	5.4 nm	(10.0) km
Range at which a 16 mm/hr rain echo exceeds threshold	4.9 nm	(9.1) km

o Ka-band Radar. - The ranges at which Requirement (a) is met are listed in Table II-73 These are obtained from Table III-14 of Section 6, Volume III.

TABLE II-73. RANGE (nm)* AT WHICH TERRAIN SIGNAL/NOISE IS GREATER THAN 20 dB AT Ka BAND

Pulse Length	Rainfall Rates				Fog Densities	
μ sec	0 mm/hr	1 mm/hr	4 mm/hr	16 mm/hr	400 ft	100 ft
1.0	19 (36)	9.7(18)	4.8(8.8)	1.9(3.5)	8.6(16)	4.0(7.4)
0.5	12 (23)	7.0(13)	3.8(7.1)	1.7(3.1)	6.5(12)	3.2(6.0)
0.1	4.3(7.9)	3.2(6.0)	2.2(4.1)	1.1(2.1)	3.1(5.8)	1.9(3.6)

The effect of rain and fog on the detection range of high ground is quite serious at Ka-band. Table II-73 shows that with a 1.0 μs pulse, the ranges in 4 mm/hr and 16 mm/hr are 4.8 and 1.9 nm, respectively, and it is only 4.0 nm in 100 ft. visibility fog. The ranges are even lower with shorter pulse lengths.

The threshold level that meets Requirement (b) is obtained from Equations (23) and (29) of Section 6, Vol. III and is given in the following table for various ranges and pulse lengths.

* Ranges are given both in nm and km (kilometers in parentheses)

TABLE II-74. THRESHOLD LEVEL (-dBW) AT Ka BAND

Range km (nm) *	Pulse Length 1.0 μs	0.5 μs	0.1 μs
1 (0.54)	75.34	78.34	85.34
2 (1.08)	92.48	95.48	98
4 (2.16)	108	105	98
10 (5.39)	108	105	98
20 (10.78)	108	105	98

The amplitude of the rain front signal is given by Equation (34) of Section 6, Vol. III and from this we derive the following values for various ranges and pulse lengths with circular polarization.

TABLE II-75. RAIN-FRONT SIGNALS (-dBW) AT Ka BAND

Range km (nm) *	Rainfall Rates: 1 mm/hr rain-front 1.0 μs	0.5 μs	0.1 μs	4 mm/hr rain-front 1.0 μs	0.5 μs	0.1 μs	16 mm/hr rain-front 1.0 μs	0.5 μs	0.1 μs
1 (0.54)	79	82	89	71	74	87	64	62	74
2 (1.08)	85	88	95	77	80	87	70	73	80
4 (2.16)	91	94	101	83	86	93	76	79	86
10 (5.39)	99	102	109	91	94	101	84	87	94
20 (10.78)	105	108	115	97	100	107	90	93	100

At ranges below the heavy line the rain-front signal is above the threshold level and, hence, produces a false warning. Figure II-23 shows that with a pulse length of 1.0 μs, 1 mm/hr rain echoes are greater than the threshold at ranges greater than 0.9 nm. With rainfall densities of 4 mm/hr and greater, the rain echo exceeds the threshold from ranges of less than 0.5 nm.

When 'typical' conditions are assumed the improvement in performance is illustrated in the following table.

TABLE II-76. TYPICAL HGA PERFORMANCE OF THE Ka BAND RADAR WITH A (1.0 μs) PULSE LENGTH

Range of high ground detection through 1 g/m^3 cloud, or fog	8.0 nm	(14.8) km
Range of high ground detection through 16 mm/hr rain	2.4 nm	(4.4) km
Range at which a 1 mm/hr rain echo exceeds the threshold	1.0 nm	(1.9) km
Range at which a 4 mm/hr rain echo exceeds the threshold	1.3 nm	(2.4) km

o V-Band Radar. - From Table III-14 of Section 6, Volume III, the ranges at which Requirement (a) is met are listed below for various weather conditions.

TABLE II-77. RANGE (nm)* AT WHICH TERRAIN SIGNAL/NOISE IS GREATER THAN 20 dB WITH V-BAND

Pulse Length						
	Rainfall Rates				Fog Densities	
μ sec	0 mm/hr	1 mm/hr	4 mm/hr	16 mm/hr	400 ft	100 ft
1.0	5.9(11)	3.0(5.5)	1.8(3.4)	0.9(1.7)	3.2(6.0)	1.1(2.1)
0.5	3.9(7.3)	2.3(4.3)	1.5(2.8)	0.8(1.4)	2.5(4.7)	1.0(1.8)
0.1	1.4(2.5)	1.1(2.0)	0.8(1.5)	0.4(0.8)	1.2(2.2)	0.5(1.0)

This table shows that the range, even in 400 ft. fog, is unacceptably low.

* Ranges are given both in nm and km (kilometers in parentheses)

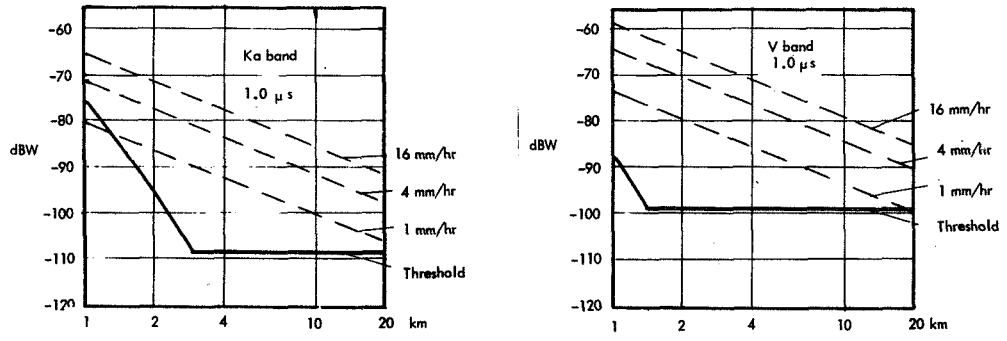

Figure II-23. Amplitude of Rain Echoes -- Ka and V Bands

The threshold level that meets Requirement (b) is obtained from Equations (24) and (30) of Section 6, Volume III and these are listed in the following table.

TABLE II-78. THRESHOLD LEVEL (-dBW) AT V-BAND

Range km (nm) *	Pulse Length		
	1.0 us	0.5 us	0.1 us
1 (0.54)	87.7	90.7	88
2 (1.08)	99	96	88
4 (2.16)	99	96	88
10 (5.39)	99	96	88
20 (10.78)	99	96	88

Equation (35) of Section 6, Volume III gives the amplitude of the rain-front echo. By substitution we obtain the following table listing the echo amplitude at various ranges, for various rainfall densities and for various pulse lengths.

TABLE II-79. RAIN-FRONT SIGNAL (-dBW) AT V-BAND

Range km (nm) *		Rainfall Rates								
		1 mm/hr rain-front			4 mm/hr rain-front			16 mm/hr rain-front		
		1.0 μs	0.5 μs	0.1 μs	1.0 μs	0.5 μs	0.1 μs	1.0 μs	0.5 μs	0.1 μs
1	(0.54)	73.8	76.8	83.8	64.8	67.8	74.8	58.8	61.8	68.8
2	(1.08)	79.8	82.8	89.8	70.8	73.8	80.8	64.8	67.8	74.8
4	(2.16)	85.8	88.8	95.8	76.8	79.8	86.8	70.8	73.8	80.8
10	(5.39)	93.8	96.8	103.8	84.8	87.8	94.8	78.8	81.8	88.8
20	(10.78)	99.8	102.8	109.8	90.8	93.8	100.8	84.8	87.8	94.8

At ranges above the thick line the rain echo is above the threshold level and false signals occur. This is also illustrated in Figure II-23 which shows that the echo from rainfall of densities of 1 mm/hr and greater is well above the threshold level over the range of 0.5 to 10 nm.

With 'typical' figures the performance is given in the following table.

TABLE II-80. TYPICAL HGA PERFORMANCE WITH THE V-BAND RADAR WITH A (1.0 μs) PULSE LENGTH

Range of high ground detection through 1 g/m^3 cloud, or fog	2.5 nm	(4.6) km
Range of high ground detection through 16 mm/hr rain	1.2 nm	(2.2) km
Range over which a 16 mm/hr rain echo exceeds the threshold	0.5 to 5.4 nm	(0.9) to (10.0) km
Range over which a 4 mm/hr rain echo exceeds the threshold	0.5 to 2.7 nm	(0.9) to (5.0) km
Range over which a 1 mm/hr rain echo exceeds the threshold	0.7 to 1.1 nm	(1.3) to (2.0) km

Optimum Frequency Band. - The calculations show that the best performance is obtained with a long pulse length regardless of frequency band. Consequently, it is assumed that a 1.0 μs pulse length will be used; the related performance to be expected is shown in Tables II-81, 82, and 83.

TABLE II-81. RANGE (nm) AT WHICH HIGH GROUND IS DETECTED -- (1 μs) PULSE LENGTH

		Frequency Band			
		X	Ku	Ka	V
Rain	4 mm/hr	22	13	4.8	1.8
	16 mm/hr	12	5.1	1.9	0.9
Fog, 100' Theoretical Parameters		18	11	4.0	1.1
Heavy Fog ($1g/m^3$) 'typical' parameters		38	22	8	2.5

TABLE II-82. RANGE (nm) AT WHICH RAIN ECHO IS ABOVE THRESHOLD LEVEL -- (1 μs) PULSE LENGTH. (Rain Echo Exceeds Threshold for Ranges Greater than the Values Shown)

		Frequency Band			
		X	Ku	Ka	V
Rain	1 mm/hr	6.5	3.8	0.9	0^+
	4 mm/hr	1.5	1.6	0.5	0^+
	16 mm/hr	0^+	0.8	0^+	0^+

TABLE II-83. RANGE (nm) AT WHICH RAIN ECHO IS ABOVE THRESHOLD LEVEL -- (1 μs) PULSE LENGTH, TYPICAL PARAMETER

		Frequency Band			
		X	Ku	Ka	V
Rain	1 mm/hr	—	—	Greater than 1.0	Between 0.7 and 1.1
	4 mm/hr	—	—	Greater than 1.3	Between 0.5 and 2.7
	16 mm/hr	Greater than 8	Greater than 4.9	—	Between 0.5 and 5.4

Table II-81 shows that the range at which high ground is detected falls off rapidly with an increase in frequency. At V-Band it is unacceptably low, even assuming 'typical' conditions. The Ka-band radar's range is marginal for an HGA system - it is between 4 and 8 nm in conditions of poor visibility. Both the X and Ku-band radars have adequate range capability.

Although the detection range with the Ka-band radar may be adequate, Tables II-82 & II-83 show that the echoes from rainfall rates of 4 mm/hr and greater can seriously affect performance by producing false warnings. The X and Ku-band radars are not affected as greatly in this respect and have comparable performance. This is due to the use of circular polarization of Ku-band off-setting the increase with frequency of the radar cross section of rain.

It can be concluded that there is little to choose between X and Ku-bands, either is suitable for an HGA radar having a performance meeting the needs of civil aircraft.

The performance of a radar in the high ground avoidance mode is not appreciably affected by changes in the antenna's horizontal aperture. A narrow antenna beam is not required for precise angular resolution in the horizontal plane and the main effect of a change in antenna size is on antenna gain which changes the detection range. For example, reducing the horizontal aperture from 1m to 0.5m would reduce the detection range by 20% and this would be acceptable both with the X and Ku-band radars. Increasing the aperture to 1.5m would increase the detection range by 15%.

o Turning Flight. - In order to continue to display ground above a horizontal clearance plane when the aircraft is banked during a turn, the antenna should be roll stabilized or, alternatively, artificially roll stabilized by suitably varying pitch angle with azimuth angle. The latter is attractive since it avoids the complexity of a roll stabilization axis.

It is also desirable during turning flight to lead the antenna into the turn by an amount which depends upon the radius of the turn in order for the ground on either side of the curved flight path to be examined. This is illustrated in Figure II-24. When the antenna scans about the fore and aft axis of the aircraft, the section AB of the flight path is examined for high ground, but when the antenna is led into the turn, the section examined is increased to AC.

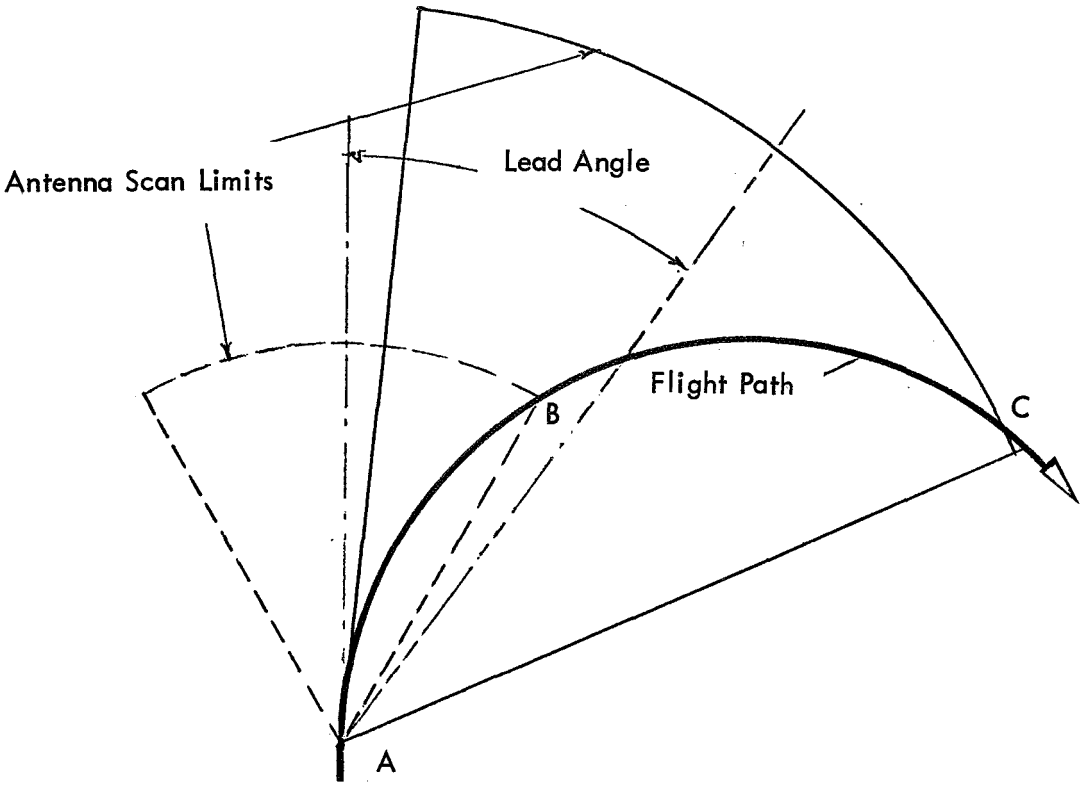

Figure II-24. Antenna Lead Angle During Turning Flight

o Interference. - An interference signal from another radar on the same frequency can produce a false alarm when its amplitude is above the threshold and when it occurs in the 0 to 5 nm range period. Whether an interference signal would indeed produce a false alarm or would be rejected depends upon the precise form of signal processing and display (visual or aural) that is used.

TABLE II-84. AIRCRAFT SEPARATION AT WHICH SIDE-LOBE TO SIDE-LOBE INTERFERENCE OCCURS

Frequency Band	Separation
X	25 nm (46) km
Ku	39 nm (72) km
Ka	13 nm (24) km
V	3 nm (5.6) km

The most likely cause of interference is occasioned by side-lobe to side-lobe transmission. The amplitude of this interference is given by Equations (21 to 24), Section 6, Vol.III, and the range at which this is equal to the 5 nm threshold level is given in Table II-84. These are the ranges for clear weather; in fog and rain they will be lower. Both enroute and on the approach there can be a number of aircraft within interference range, especially with the X and Ku band radars.

When the antenna beam of one aircraft is pointing at a second aircraft, the amplitude of the interference signal is considerably increased and interference can occur when aircraft are within optical range. The probability of interference occuring with the X-band radar is, for example,

1 in 24, due to antenna beamwidth, 2.5°, and scan angle, 60°.

1 in 10, if magnetrons frequencies are spread over 10 channels.

1 in 20, with a detection range of 5 nm and a pulse repetition frequency of 1000Hz.

This gives an overall probability of a false warning due to interference from another aircraft within optical range of 1 in 4800, at X-band.

When both beams are pointing at each other the interference still occurs when the aircraft are within optical range but the probability is reduced to 1 in 115200 at X band.

Table III-33, Section 7, Vol. III shows that on the approach path, signals reflected from the ground from one aircraft to another can cause interference. This is significant only when both beams illuminate the same patch of ground and the probability of this is low.

Although the probability of interference from another aircraft is low, along busy air routes and near airports, the number of aircraft within interference range could be large and, hence, it will be necessary to use interference rejection circuits to prevent false warnings. These operate by supressing the first received pulse unless, after a number of transmitter pulses, a given percentage has been received at the same range. In this way, interference signals which move in range from pulse to pulse because of non-synchronized pulse repetition frequencies are eliminated.

6.5 Specific Functions

In this section, several specific functions of the overall hazard warning and avoidance system are briefly discussed. Among these functions are the monitoring of the landing approach with respect to the desired glide path, the detection of obstacles on the runway and the assistance of roll out and taxi.

6.5.1 Glide Slope Monitoring in the Elevation Plane. - The simplest way to monitor vertical position on the glide path is to compare computed required height with measured height. Required height may be found by multiplying Slant Range to Threshold, as seen by the radar, with the sine function on the intended glide slope, i.e., sin 3°. Measured height could be derived by reference to a radar altimeter (over level terrain) or pressure altimeter corrected for pressure altitude variation and height of runway above sea level. However, these two methods rely upon the usual aircraft systems and do not furnish a truly independent measure of altitude.

A method which is more in keeping with the desire for independent measurement would be to obtain angular information in the elevation plane from the radar. For the required accuracy of 0.37° (See Section 4), a monopulse or interferometer technique must be used. With such a system, it is possible to show on a display, the position where the boresight intercepts the ground with an angular accuracy of about one twentieth the elevation beamwidth (Ref.35). This gives for the radars considered in this report, a boresight error of 0.38° at X-band, 0.23° at Ku-band and 0.20° at Ka and V-bands.

When the antenna is pitch-stabilized so that the boresight is depressed from the horizontal by an angle which is equal to the glide path angle, the aircraft is on the glide path when the boresight intercepts the desired touchdown point. In order to identify the touchdown point on the display a marking is placed at the appropriate distance from the runway threshold.

In the case of the enhanced runway, numerous reflector (beacon) patterns are possible and the need will exist to develop a display system which allows display of the monitor information to the pilot in a form which is quickly understood. Foremost, at the concept stage, is a set of points or lines which synchronize with the returns from the reflectors when the landing is proceeding satisfactorily. If one reflector is adjacent to the desired touchdown point, the radar monitor can track that reflector for vertical guidance.

With a system in which the radar is locked on to the reflector at the touchdown point, the necessary angular information is obtained from the angular position of the antenna. It should be noted that this system requires monopulse capability in the azimuth plane as

well as in the elevation plane so that the reflector or transponder can be tracked.

6.5.2 Detection and Recognition of Obstacles on Runway. - Introduction. - An obstacle on the runway large enough to hazard a landing aircraft is likely to have a radar cross section of 1 meter^2. Such an obstacle could be detected by a radar when the signal from the object is well above the signal from the ground adjacent to the runway at the same range. If we assume that this margin is 10 dB then the requirements to be met are as follows:

Requirements:

(a) Signal from terrain adjacent to runway to be greater than 10dB above receiver noise.

** (b) Signal from target of 1 meter^2 or greater, to be greater than 10dB above signal from terrain adjacent to runway.

(c) Signal from terrain adjacent to runway to be 10dB above that from rain front at same range.

• Detection Range. - Tables III-13 and III-14, Section 6, Vol. III give the ranges at which Requirements (a) and (c) are met. The range at which Requirement (b) is met is obtained by substitution into Equations (65) to (68) of Section 6, Volume III.

A cursory examination shows that Requirement (b) is the limiting requirement for all frequency bands; the ranges at which this requirement is met as a function of frequency are listed in Table II-85. *

Note: ** This is the limiting requirement for detection of a 1 m^2 obstacle on the runway.

* This table clearly shows that a radar of the types considered will not detect an obstacle of 1 meter^2 cross-section on the runway at a range which is great enough for the pilot to take avoiding action or to abort the landing. However, when proceeding along the taxiway, a 0.1 μs pulse length should provide a detection range which would be adequate for the detection of an obstacle such as another aircraft or small highway vehicle.

TABLE II-85. RANGE (ft) AT WHICH SIGNAL FROM TARGET OF 1 m^2 CROSS SECTION IS 10 dB ABOVE SIGNAL FROM TERRAIN AT SAME RANGE

Frequency Band	Pulse Width	Range in feet at which $S_c/S_t = 10$ *
X	1.0	18 (5.7)
	0.5	37 (11.4)
	0.1	187 (57)
Ku	1.0	30 (9.3)
	0.5	61 (18.6)
	0.1	305 (93.0)
Ka	1.0	65 (20.0)
	0.5	131 (40.0)
	0.1	656 (200.0)
V	1.0	131 (40.0)
	0.5	262 (80.0)
	0.1	1312 (400.0)

* Range is given both in feet and meters (meters within parentheses)

6.5.3 Performance of Landing Monitor During Taxi Phase. - An aircraft equipment that provides a radar map of an airport with sufficient definition for it to be used as an IALM should be able to provide an aircraft on the ground with mapping information to enable it to proceed along the taxiway to the terminal under conditions of poor visibility. The range the radar requires on the ground is very much less than that which is required in the air. It will depend upon the taxi speed and the complexities of the taxi track but 500 to 1000 ft. would probably be adequate. It is, of course, important for the minimum range to be as low as possible and for this a narrow pulse length must be used. With a pulse length of 0.1 μ s, it should be possible to make the minimum range capability less than 100 ft.

The X-band radar with a 2.5° azimuth beamwidth, has a pulse packet width of 40 ft. at a range of 1000 ft.; thus, the definition this provides is not adequate. However, the azimuth resolution obtained with the Ku, Ka and V-band radars should be good enough.

Because the maximum range is only 1000 ft., the performance is not seriously affected by fog. At V band, for example, the two way attenuation in 100 ft. visibility fog is only about 3 dB at a range of 1000 ft.

The pilot's task might be made somewhat easier if corner reflectors were deployed to identify the taxiway and, as suggested earlier, it is possible to use space coded groups to remove extraneous signals and to identify a particular taxiway. The size of the corner reflector required to give a signal 10 dB above that from the surrounding terrain, at a range of 1000 ft., is given by Equations (81) to (84) of Section 6. Table II-86 lists corner reflector size requirements for different frequency bands, all operating at a pulse length of 0.1 μs.

TABLE II-86. CORNER REFLECTOR SIZE FOR 10 dB REFLECTOR SIGNAL TO TERRAIN SIGNAL AT 1000 ft. PULSE LENGTH (0.1 μs)

Frequency Band	Echoing Area, m^2	Reflector side Dimension, cm
X	5.4	18.4
Ku	3.2	12.8
Ka	1.5	7.1
V	0.8	4.3

This table shows that the reflector size required is very much smaller than that needed to identify a runway for a landing system and, hence, should not confuse a pilot landing an aircraft.

As regards other aircraft or vehicles on the taxiway, Section 6.5.2 shows that a radar with a pulse length of 0.1 μs detects an obstacle with a radar cross section of 1 $meter^2$ at a range of approximately 150 ft. at X band, 280 ft. at Ku band, 600 ft. at Ka band, and 1200 ft. at V band. This capability should give adequate warning of the proximity of other aircraft or airport vehicles on the taxiway.

6.5.4 Physiological and Other Consequences of Using the Radar in the Taxiway and Ramp Areas. - When aircraft are on the ground and the nose radar is switched on, ground personnel can be subjected to microwave radiation. The mean power density of the radiation near the antenna is given in the following table. A duty cycle of 0.001 has been assumed.

TABLE II-87. MEAN RADIATION POWER DENSITY

Frequency Band	Peak Power kW	Mean Power mW	Antenna Aperture cm^2	Power Density mW/cm^2
X	20×10^3	20×10^3	3×10^3	6.7
Ku	20×10^3	20×10^3	3×10^3	6.7
Ka	20×10^3	20×10^3	1.5×10^3	13
V	10×10^3	10×10^3	8×10^2	12

These power densities which extend to the Rayleigh distance from the antenna ($a^2/2\lambda$) are listed in the following table.

TABLE II-88. RAYLEIGH DISTANCE FROM ANTENNA

Frequency Band	Rayleigh Distance feet *
X	56 (17)
Ku	89 (27)
Ka	198 (60)
V	463 (140)

* Ranges are given both in feet and meters (meters in parentheses)

The Maximum Safe Exposure Level (MSEL) officially specified by the US Armed Services is $10 mW/cm^2$ (Ref. 36). Thus it is seen that the radiation from the X and Ku-band radars is below the danger level. But the Ka and V-band radars have radiation levels slightly above the maximum permitted value out to ranges of 60 and 140 meters, respectively, from the antenna. If one postulates an efficiency for the Ka and V band antennas of something approaching 50%, radiation is reduced to a level which is below the maximum specified figure. It would only become a problem if the MSEL were lowered further (Ref. 36).

Another ramification of the emission of microwave radiation in the terminal area is the possibility of damaging other radar equipments fitted to other aircraft on the ground. For example, an unprotected X-band radar which was inadvertently pointed at a second transmitting, 20kW X-band radar, could receive sufficient energy to burn out its mixer

crystals. For this event to occur the equipment receiving the radiated energy would have to be in a switched-off mode and not protected by passive T/R Limiters and/or mechanical shutter. Since it is now standard practice to fit airborne radar with these protective devices, the radiation hazard on other radars is assumed not to be a problem.

The effects of the radar radiation on both personnel and other equipments can also be reduced by operating the radar in a low power mode during taxi operations. The needs during taxi are for relatively short range operations and a low power mode could be both convenient and useful.

6.6 Recommended Frequency Band for Combined ILM and HGA Radar

6.6.1 Introduction . - So far in this report ILM and HGA systems have been considered separately and it is shown that best performance of each is obtained on different frequency bands. However, both these systems need large forward looking antennas installed in the nose of the aircraft and, because of the limited space available, this presents serious installation problems. There is also the cost consideration. It is unlikely that an airline would pay for two radars, in addition to the weather radar. A possible solution would be to use a common antenna aperture for the two frequency bands. This would minimize the installation problem, but would be expensive.

There is, therefore, a strong case for meeting both the ILM and HGA requirements with one radar. Naturally, with a common equipment there will be some degradation in performance in the two modes. This is considered below.

Although the maximum ranges in the HGA and ILM modes are the main criteria for deciding which is the optimum frequency band, there are other features which may affect the choice. These other features are listed below together with an indication of how these change with frequency. The band which gives the best performance is indicated with a circle; an X indicates that performance is very unsatisfactory. This table is used when it is difficult to obtain a clear choice of optimum frequency band just from the range performance.*

TABLE II-89. OPTIMUM FREQUENCY BAND FOR VARIOUS CONDITIONS (Other than ILM or HGA)

FREQUENCY BAND	X	Ku	Ka	V
Interference				○
Obstacle Detection in HGA		○		
Radar Complexity		○	○	○
Taxiway Guidance:				
Without Reflectors	×			○
With Reflectors	○	○	○	○
Obstacle Detection	○			
Radiation Hazard	○	○		

*Ranges in this section are given both in nautical miles (nm) and kilometers (km). Kilometers are in parentheses.

6.6.2 Runways Without Enhancement. - For an equipment that has to operate against runways not enhanced with reflectors or beacons, the only frequency bands that can be considered are Ka and V. With X and Ku bands the detection range of 150 ft runways is less than 1 nm because of beamwidth limitation and this is obviously inadequate.

It has been shown that a radar designed to have a minimum range of 100 ft has a very poor detection range especially with V band. It is, therefore, of interest to examine, in addition, the performance when the minimum range required is 800 ft. This is obtained with a 1 μs transmitter pulse length. The "theoretical" performance obtained with this radar is listed in Table II-90. Also listed is "typical performance" expected in practice. The following assumptions have been made in deriving the "typical performance."

(1) Water content in fog is half theoretical value.

(2) Rain cross section is 10dB below theoretical figure.

(3) Angle of grazing with high ground is 30° in HGA mode.

TABLE II-90. PERFORMANCE OF THE Ka AND V-BAND RADARS IN HGA AND ILM MODES (PULSE LENGTH 1.0 μs)

MODE	PERFORMANCE			
	"THEORETICAL"		"TYPICAL"	
	Ka	V	Ka	V
HGA				
Range in 100 ft fog, nm	4.0 (7.4)	1.1 (2.0	8.0 (14.8)	2.5 (4.6)
Range in 16 mm/hr rain, nm	1.9 (3.5)	0.9 (1.7	2.4 (4.4)	1.2 (2.2)
False returns from 4 mm/hr rain	Yes	Yes	No	Yes
ILM				
Range in 800 ft fog, nm	4.8 (8.9)	9.6 (17.8	4.8 (8.9)	9.6 (17.8)
Range in 100 ft fog, nm	4.8 (8.9)	1.5 (2.8	4.8 (8.9)	3.2 (5.9)
Range in 16 mm/hr rain, nm	0.1 (0.18)	0.008(0.01	1.0 (1.9)	0.08 (0.15)

This table shows that the V band radar has good ILM performance in visibility conditions down to 800 ft., but the detection ranges in the HGA mode, where it is essential to operate in 100 ft. visibility fog, are low.

For taxiway guidance the transmitter pulse length must be reduced to 0.1μs. It is relatively simple to design a radar so that the pulse length can be switched from 1.0 to 0.1μs, but considerable complexity is involved in changing the receiver bandwidth from 1 to 10MHz, so as to maintain this at its optimum value. It is suggested, therefore, that the receiver bandwidth is kept constant at 10MHz. The effect this has on the performance is shown in the following table.

TABLE II-91. PERFORMANCE OF THE Ka AND V-BAND RADARS WITH A TAXIWAY GUIDANCE CAPABILITY

MODE	PERFORMANCE			
	"THEORETICAL"		"TYPICAL"	
	Ka	V	Ka	V
HGA 1.0μs				
Range in 100 ft fog, nm.	2.9 (5.3)	0.9 (1.6)	6.0 (11.1)	1.3 (3.3)
Range in 16 mm/hr rain, nm.	1.4 (2.6)	0.6 (1.1)	1.9 (3.5)	0.9 (3.5)
False returns from 4 mm/hr rain .	Yes	Yes	No	Yes
IALM 150 ft Concrete Runway				
1.0 s Transmitter Pulse				
Detection Range in 800 ft fog, nm	4.8 (8.9)	9.6 (17.8)	4.8 (8.9)	9.6 (17.8)
Detection Range in 400 ft fog, nm	4.8 (8.9)	3.2 (5.9)	4.8 (8.9)	4.9 (9.1)
Detection Range in 100 ft fog, nm	4.8 (8.9)	1.4 (2.6)	4.8 (8.9)	1.9 (3.5)
Detection Range in 16 mm/hr rain, nm	0.1 (0.18)	0.008(0.015)	1.0 (1.8)	0.08 (0.15)
0.1 μs Transmitter Pulse				
Detection Range in 400 ft fog, nm	3.2 (5.9)	1.1 (2.0)	4.8 (8.9)	1.9 (3.5)
Detection Range in 100 ft fog, nm	2.9 (5.4)	0.9 (1.7)	4.3 (8.0)	1.2 (0.15)
Detection Range in 16 mm/hr rain, nm	0.1 (0.18)	0.008(0.015)	1.0 (1.9)	0.08 (0.15)

This table shows that the detection range of the V band radar in the HGA mode is too short, even assuming "typical" conditions. Hence for an equipment that has to provide both HGA and IALM modes the only suitable band is Ka. The change in the detection ranges in the IALM mode with transmitter pulse length is not significant under "typical" conditions and, therefore, it is proposed that the same pulse length of 0.1μs is used for the approach and landing phase and for the taxi phase.

Reducing the horizontal aperture of the antenna to 0.5m to accommodate a smaller aircraft would reduce the HGA ranges by 20% and, because of the increase in the azimuth beamwidth, the runway detection range of the Ku band radar in the IALM mode would be reduced to 2.2nm.

Increasing the horizontal aperture to 1.5m if installation space allowed, would increase the range in fog in the HGA mode by 15%, but this would still not make the performance of the V band radar adequate. The range of the Ka band radar in the IALM mode on 150 ft runways would also increase by approximately 15% in fog. The performance in rain would not be affected by this change in aperture size. Therefore, a 1.5m aperture does not appear to hold a significant advantage over a 1.0m aperture.

6.6.3 Runways With Enhancement. -

Runways With Corner Reflectors. - The range of the V band radar in a 100 ft. visibility fog and in 16mm/hr rain is unacceptably low in both the ILM and HGA modes. With Ka band the performance is marginal in both modes; but good detection ranges are obtained at X and Ku bands. The Ku band is the better choice of these two since it requires the smaller corner reflector. Furthermore, Table II-89 shows that Ku is the better of the two.

The optimum pulse length for the HGA mode is 1.0us and for the ILM mode it is 0.1μs. The transmitter should, therefore, be designed so that the pulse length can be switched to either of these two values. As discussed in Section 6.6.2, it is impracticable to make a corresponding change to the receiver bandwidth in order to maintain it at its optimum value and it is, therefore, suggested that it should be made 10MHz wide. The performance of such an equipment is given in the following table.

This equipment also gives good taxiway guidance when switched to a pulse length of 0.1μs.

TABLE II-92. PERFORMANCE OF THE Ku BAND RADAR IN HGA AND ILM MODES
(Runway Enhanced with Reflectors)

MODE	"THEORETICAL" * PERFORMANCE	"TYPICAL" * PERFORMANCE
HGA (1.0 μ s)		
Range in 100 ft fog	7 (13.0)	14 (25.9)
Range in 16 mm/hr rain	3.8 (7.0)	5.0 (9.3)
False Returns from 16 mm/hr rain fronts	Yes	No
ILM (0.1 μ s) 22m^2 Reflector		
Range in 100 ft fog, nm	10 (18.5)	10 (18.5)
Range in 16 mm/hr rain, nm	5.4 (10.0)	5.4 (10.0)

*"Theoretical" and "Typical" are consistent with the definition set down in the previous Section, Runways Without Enhancement.

Runways with Beacon Transponders. - Page 59 of Volume III shows that the beacon transmitter power required increases rapidly with frequency. That required for V-band is impracticably large, but for the other bands the power required can now be achieved with solid state sources.

As regards HGA performance, X and Ku bands give satisfactory performance, but Table II-93 shows that when other performance factors are taken into consideration, Ku is the better choice.

The pulse length for HGA should be 1.0μs, but for the ILM mode, 0.1μs is probably the best value and this can also be used for taxiway guidance. As described in the previous topic, the receiver bandwidth should be 10 MHz in order to allow for the 0.1μs pulse and, in order to reduce complexity, this is also used when the pulse length is 1.0μs. The performance obtained with this system is listed in Table II-94.

TABLE II-93. PERFORMANCE OF THE Ku BAND RADAR IN HGA AND ILM MODES
(Runway Beacons)

MODE	"THEORETICAL" PERFORMANCE	"TYPICAL" PERFORMANCE
HGA (1.0 μs)		
Range in 100 ft fog	7.0 (12.9)	14 (25.9)
Range in 16 mm/hr rain	3.8 (7.0)	5.0 (9.3)
False Returns from 16 mm/hr rainfronts	Yes	No
ILM (0.1 μs) 81mWBeacon		
Range in 100 ft fog	24 (44.4)	40 (74.0)
Range in 16 mm/hr rain	10 (18.5)	10 (18.5)

With a beacon power of 81mW, ILM operates satisfactorily in 16mm/hr rain as well as in 100 ft. visibility fog and, since it is a beacon system, there are no rain echoes to confuse the pilot.

The performance would be altered if either a larger or smaller installation space were considered. Reducing the antenna horizontal aperture from 1m to 0.5m would reduce the HGA ranges by 20% and the IALM ranges by 30%. On the other hand, increasing the aperture to 1.5m would increase the HGA ranges by 15% and the IALM ranges by 23%.

6.6.4 Alternative Solution. -

- Introduction

An alternative solution that is worthy of consideration is a single equipment that has weather radar, HGA, ILM and taxiway guidance capabilities. This is attractive since it overcomes the problem of finding space in the nose of an aircraft for a multiple antenna installation and because it reduces the complexity and cost of the equipment required.

To meet weather radar requirements it is most likely that X band would have to be used and such a system is considered below. But for certain applications, Ku or C band is a possibility and there is no reason why this solution should not be adopted on these bands.

Because of its wide azimuth beamwidth and ILM system that operates on X band is not satisfactory without some form of runway enhancement. Although beam sharpening improves the angular resolution with point targets and with beacons, it does not improve runway definition as seen on a radar map of the airport. Consequently, this system requires reflectors or beacons to identify the runway and taxiway.

- Antenna Requirements

  The main antenna requirements are as follows:

  (1) Weather Radar

  Pencil beam, typically 3° wide.

  Azimuth scan ± 90°.

  Pitch stabilized with respect to the horizontal.

  (2) HGA

  Pencil beam in azimuth.

  Beam sharpening required in elevation plane to give angular accuracy of 0.3°

  Azimuth scan, greater than ± 30°.

  Boresight pitch stabilized with respect to horizontal or flight vector.

  (3) ILM

  Beam sharpening required in elevation plane for angular accuracy of 0.3°.

  Beam sharpening required in azimuth plane for angular accuracy of 0.4°.

  Azimuth scan, greater than ± 30°.

  Elevation boresight pitch stabilized with respect to the horizontal.

  (4) Taxiway Guidance

  Beam sharpening required in azimuth plane for angular accuracy of better than 1.5°.

  Azimuth scan, greater than ± 30°.

An antenna that has beam sharpening in both azimuth and elevation planes is capable of meeting all the above requirements and this can be provided either by monopulse or interferometer techniques. Both these are well known and have been extensively used in military systems.

- Transmitter/Receiver Requirements

The transmitter pulse length of a weather radar is usually several microseconds long and the receiver bandwidth correspondingly narrow in order to obtain adequate range. There is no reason why the same pulse length should not be used for HGA but, as discussed earlier, for ILM and taxiway guidance the pulse length should be much shorter, for example 0.1μs, with a 10MHz receiver bandwidth. This is achieved quite easily by designing the transmitter so that the pulse length can be switched, for example from 5μs to 0.1μs. With the short pulse length, a wide band sum receiver is required, in addition to the two wide band receivers associated with the monopulse difference, or interferometer channels.

- Performance

Since only one equipment has to be installed in the nose of the aircraft, there is no reason to limit its transmitter power to 20kW in order to cut down its size and it could be increased to about 70kW, which is typical of weather radar equipments fitted to civil aircraft. In this case its weather radar performance would be similar to that of a typical 70kW weather radar.

In the HGA and ILM modes its performance is slightly changed from that of the X band equipments considered earlier in the report because of difference in the parameters. When these are substituted in the appropriate equations of Vol. III, Section 6, we find that the performance is as listed in Table II-94. This is for a monopulse system with an antenna diameter of 3 feet, and parameters as listed. The parameters not listed are the same as those in Table III-11 of Volume III.

This table shows that satisfactory performance is obtained with an X band equipment in the HGA and ILM modes, provided beam sharpening techniques are used. If it is concluded that runway enhancement has to be used to provide acceptable performance in the ILM mode, i.e., a range of at least 5 nm on all types of runways, under all weather conditions, then an X band equipment is the best choice. As well as acting as an ILM

TABLE II-94. PERFORMANCE OF THE X BAND MULTI-MODE RADAR IN HGA AND ILM MODES

MODE	PARAMETERS		PERFORMANCE	"THEORETICAL"	"TYPICAL"
HGA	Transmitter Power	70kW	Range in 100 ft fog	21 (39) *	37 (68) *
	Pulse Length	5μs	Range in 16 mm/hr rain	13 (24)	19 (35)
	Receiver bandwidth	10MHz	False echoes in 0 to 10nm range		
	Antenna gain	33dB	From 4 mm/hr rain	Yes	No
			From 16 mm/hr rain	Yes	No
ILM	Transmitter Power	70kW	Corner Reflector		
	Pulse Length	0.1μs	Size for 10 nm Range		
	Receiver bandwidth	10MHz	In 16 mm/hr rain	$3500m^2$	$350m^2$
	Antenna gain	33dB	Beacon Power for 10 nm range in 16 mm/hr rain	1.2mW	1.2mW

it can provide HGA and weather radar information. Although the equipment is more complex than a weather radar, its cost would be much less than that of a weather radar plus a separate ILM-HGA radar. In addition the installation problems are considerably reduced.

In the smaller commercial aircraft where there would be space only to install an antenna with a horizontal aperture of 0.5m, the ranges of the radar in the HGA mode would be reduced by 20% and the corresponding figure in the IALM mode would be 30%. The range in the IALM mode could be maintained at 10nm in 16mm/hr rain by increasing the beacon power to 2.4mW. It is seen, therefore, as far as the HGA and IALM modes are concerned, satisfactory performance can be obtained with a small antenna having a horizontal aperture of 0.5m; in practice, the performance requirements of the weather radars will dictate the antenna size.

Large aircraft could be fitted with an antenna having a horizontal aperture of 1.5m and this would increase the ranges in the HGA and IALM modes by 15% and 23%, respectively.

* Ranges are given both in nm and km (kilometers in parentheses)

6.7 Optical Sensors

6.7.1 Introduction. - The performance of optical sensors depends upon the design parameters such as aperture size and detector sensitivity, but the main factor that limits the detection range is the attenuation and scattering rather than absorption. Attenuation reduces the amplitude of the wanted signal whereas scattering from other light sources increases the background illumination level.

Possible wavebands for optical sensors range from the visible band to the far infra-red, but in this report we shall restrict our consideration to two bands. These are the 0.5 to 1 micron band and the far infra-red wavelength of 10 microns. The reason for this is that there has been, over the past few years, extensive development of equipments on these bands for military applications.

6.7.2 Optical Sensor Systems for Runway Detection. -

Sensor Requirements. - The performance requirements of optical sensors are not necessarily the same as those for an approach and landing role. There are two main differences. First, military targets are not cooperative and sources of illumination that would help in their detection are usually absent. Airports, on the other hand, can always be assumed to have approach and runway lights. Second, operation in fog is desirable in the military case, but it is absolutely essential for an IALM. In general terms, an optical IALM sensor must operate in fog and have detection ranges on the approach and runway lights, greater than those obtained visually and unaided by the pilot.

Fog affects performance by attenuation and scattering. Attenuation reduces the intensity of the lights being viewed and this is overcome by improving the sensor sensitivity. Scattering from lights and, during the day from the sun, raises the background illumination level and reduces the contrast ratio. This reduces the range at which lights can be seen by an amount which is independent of the sensor sensitivity.

There are numerous conditions of poor visibility when one considers all the possible variations in the height and density of clouds and fogs. Analysis of all possible conditions would be a monumental task and, therefore, the investigation is limited to a few typical cases.

Active systems as well as passive systems have been developed which provide self-illumination of the target to improve night operation. But with approach lighting, this is unnecessary and, therefore, such systems are not considered.

Effect of Scattering on Sensor Range. - Consider the case, illustrated in Figure II-25 of an aircraft descending through a layer of fog having an attenuation coefficient α. The sensor is required to detect light L_1 in the presence of scatter from light L_2. During the day, detection must take place in the presence of scatter from solar radiation as well as from light L_2.

The irradiance at the sensor S from the light L_1 is given by the equation

$$H_1 = \frac{P}{(R + D)^2} \quad \text{Exp } [-\alpha (R+D)]$$

where P is the radiant intensity of the light and α is the attenuation coefficient.

As regards the background illumination, we shall assume that it is produced by scattering from the region shown shaded in Figure II-25 and, in order to simplify the calculations, it is further assumed that the forward scattering and attenuation coefficients are equal. By integration we obtain the following equation for the total scattered power density at the sensor

$$H_S = \frac{P \alpha A}{4 \pi} \cdot \frac{(5R - D)}{RD} \cdot \frac{\text{Exp } [-\alpha R]}{(R + D)^2}$$

where A is the aperture area of the light L_1.

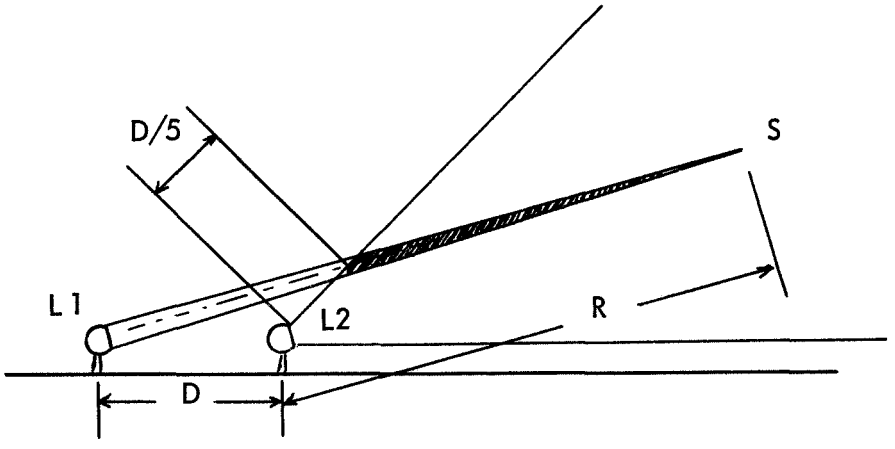

Figure II-25. Scattering in Fog.

For light L_1 to be seen, H_1 must be greater than H_s. If this ratio is taken as 2:1 then the condition for visibility is:

$$\frac{P}{(R+D)^2} \cdot \text{Exp}\,[-\alpha\,(R+D)] > 2\,\frac{P\,\alpha A}{4\pi} \cdot \frac{(5R-D)}{RD} \cdot \frac{\text{Exp}\,[-\alpha R]}{(R+D)^2}$$

$$\text{i.e.,} \qquad \text{Exp}\,[-\alpha D] > \frac{\alpha A}{2\pi} \cdot \frac{(5R-D)}{RD}$$

when $A = I\ ft^2$ and D is small compared with 5R, this simplifies to:

$$\text{Exp}\,[-\alpha D] \quad \frac{2.5}{\pi} \cdot \frac{\alpha}{D}$$

This condition is plotted in Figure II-26. It shows that as the attenuation coefficient increases there is a rapid fall in the distance at which the light ahead of the one producing the glare can be seen.

Flight trials have shown that for a landing to be carried out in poor visibility, a segment of the approach lighting at least 300 ft long must be seen by the pilot (Ref.37). Figure II-26 shows that this is only possible when the attenuation is less than $3 \times 10^{-2} ft^{-1}$. This corresponds to a meteorological visibility of about 300 ft with a 0.5 μ sensor and to 100 ft with a 10 μ sensor. These limiting visibility conditions are irrespective of the lighting intensity and the sensitivity of the sensor.

During the day glare from the sun can seriously reduce the range at which the approach lights can be seen. The main factors that affect the range are the strength of the solar radiation along the viewing path and the density of the fog or cloud.

Considering the case shown in Figure II-27, we obtain by integration the following equation for the total scattered irradiance at the sensor S in the solid angle subtended by the light L.

$$H_s = \frac{140}{40\pi} \cdot \frac{A}{R^2} \cdot \text{Exp}\,[-\alpha X] \left\{1 - \text{Exp}\,[-\alpha R]\right\}$$

where: Solar radiation = $140 Wft^{-2}$
A = Aperture area of light
α = Attenuation coefficient
$\alpha/10$ = Scattering coefficient at 90°
X = Distance optical path is below top of fog or cloud
R = Range to light

With a light of radiant intensity P Wsr^{-1} the irradiance at the sensor is:

$$H_1 = \frac{P}{R^2} \cdot \text{Exp}\,[-\alpha R]$$

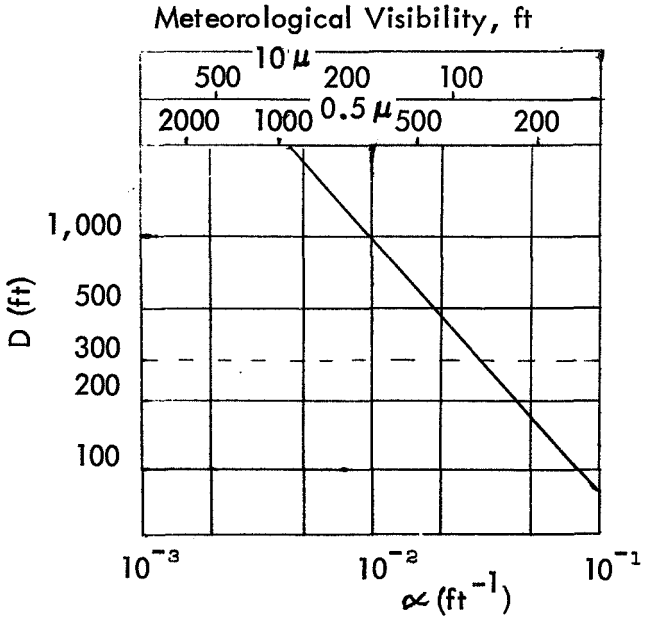

Figure II-26. Effect of Scatter on Sensor Range

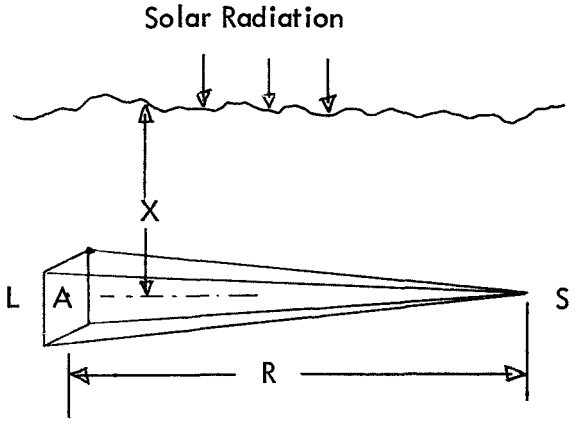

Figure II-27. Scattering from Solar Radiation

Assuming that H_1 must be more than twice H_s for the light to be seen then, neglecting the difference in the spectral distribution of the sun and approach light, the condition for visibility is:

$$\text{Exp}\,[-\alpha R] > 2\,\frac{140}{40}\cdot\frac{A}{P}\cdot\text{Exp}\,[-\alpha X]\left\{1-\text{Exp}\,[-\alpha R]\right\}$$

Substituting the typical values:

$P = 15\ \text{Wsr}^{-1}$ (10,000 candelas)

Note: (the candela and the "candle" are equivalent units)

$A = 1\ \text{ft}^2$

gives the following:

$$\text{Exp}\,[-\alpha R] > \frac{\text{Exp}\,[-\alpha X]\left\{1-\text{Exp}\,[-\alpha R]\right\}}{6.75}$$

This relationship is plotted on Figure II-28.

The important conclusion to be drawn about sun glare is that to be absolutely sure of it not affecting visibility, the distance below the top of the cloud or fog must be greater than the range of the light to be detected. It is also interesting to note that when the attenuation coefficient falls below a critical value, detection of a light at a given range is no longer affected by sun glare. For example, a light can be seen at a range of 1000 ft with a 0.5 μ sensor in fog or cloud with a meteorological visibility of 2000 ft irrespective of the height of the cloud or fog layer.

o Sensor Performance. - With a low light level TV system having a sensitivity of 10^{-8} lumens/ft^2, and assuming that the spectral distribution of the approach light matches the spectral response of the sensor, the range at which the light of P candelas is detected is given by the equation:

$$\frac{P}{R^2}\ \text{Exp}\,[-\alpha R] = 10^{-8}$$

Figure II-29 plots the detection range against attenuation coefficient for a nighttime approach light of 1000 candelas and a daytime light of 1000 candelas.

From Figures II-26, 28, and 29, the following table has been derived which lists the limiting meteorological visibilities for sensor ranges of 500 ft and 1000 ft. Also listed in parenthesis is the factor that is causing the limitation.

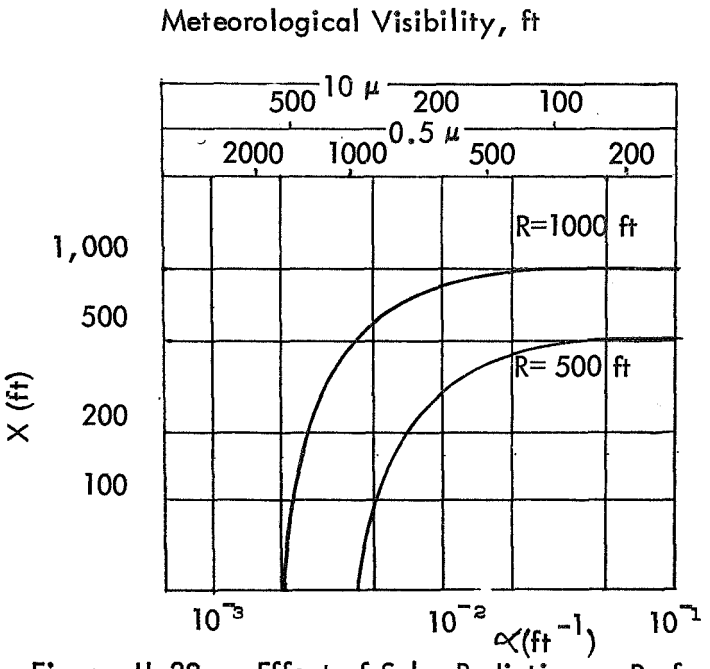

Figure II-28 . Effect of Solar Radiation on Performance

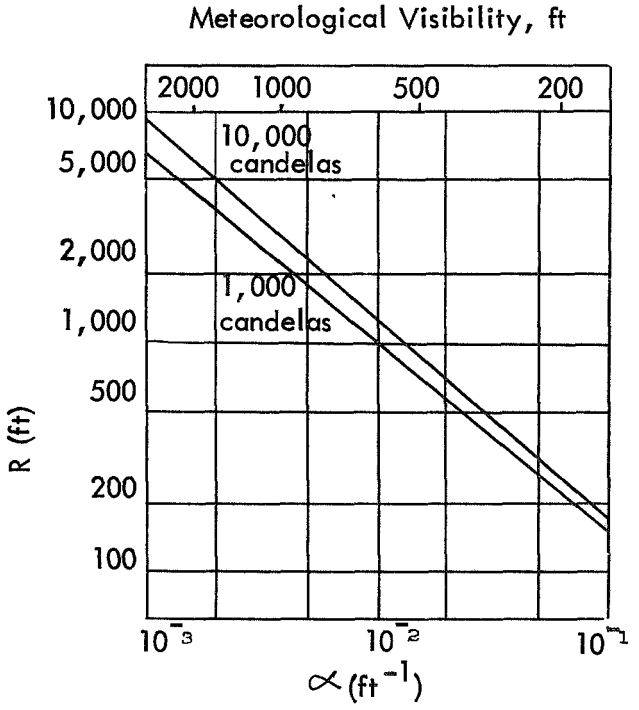

Figure II-29. LLLTV Sensor Performance

TABLE II-95. Performance of LLLTV Sensor

Range Required ft	Limiting Meteorological Visibility, ft	
	Day	Night
500	1000 (solar glare)	390 (sensitivity)
1000	1700 (solar glare)	600 (sensitivity

This table shows that the sensor range is not all that different from the meteorological visibility and when one takes into account the improvement in visual range when runway and approach lighting is used, it is obvious that little or no benefit is obtained by the use of this sensor.

Figure II-30 plots the detection range of a 10 micron sensor against attenuation coefficient. It has been assumed that the power radiated by an approach light in a frequency band corresponding to the spectral response of the detector is such that the intensity of illumination at the detector at a distance R is given by:

$$\frac{1}{10R^2} \text{ Exp } [-\alpha R] \text{ w/ft}^2 \text{ at night}$$

and $$\frac{1}{R^2} \text{ Exp } [-\alpha R] \text{ w/ft}^2 \text{ during the day}$$

It is further assumed that the sensor has a cooled detector, followed by an amplifier with a 10^5Hz bandwidth, giving an effective detectivity of 5×10^8 w^{-1}, and an aperture of 4×10^{-2} ft^2.

From Figures II-26, 28 and 30, the following table is obtained which lists the limiting meteorological visibilities for sensor ranges of 500ft and 1000ft. The factor that limits the performance is given in parenthesis.

TABLE II-96. PERFORMANCE OF INFRA-RED SENSOR

Range Required	Limiting Meteorological Visibility, ft	
ft	Day	Night
500	300 (solar glare)	300 (sensitivity)
1000	500 (solar glare)	800 (sensitivity)

This table shows that in most cases the infrared sensor has slightly greater detection ranges than the 0.5 micron sensor, but the increase over that obtained visually by the pilot is marginal.

This cursory analysis of the performance of optical sensors in the detection of runways with approach lights has shown, in the cases considered, it is not all that different from that obtained visually by the pilot. A more detailed examination may reveal that the optimum wavelength is between 0.5 and 10 microns but significant improvement is unlikely. Since these sensors are large and expensive, it is concluded that the marginal increase in the detection ranges does not justify their adoption as a landing aid.

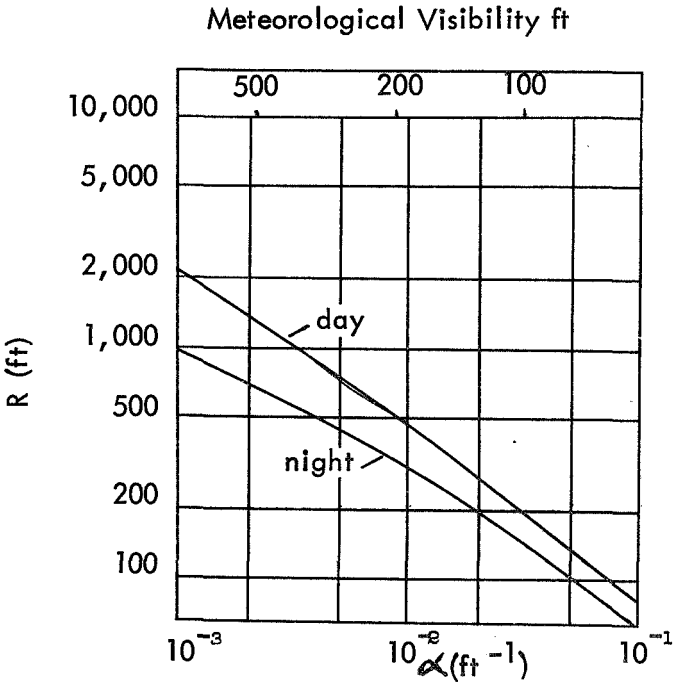

Figure II-30. Range of Infrared Sensor.

6.8 Summary

In summarizing sensor performance, the following items stand out:

1. The radar range performance on unenhanced runways falls short of the desired performance. Ka band gives the best performance of the radars studied. Its range is on the order of 3 to 5 nm in clear weather and light rain but the range capability deteriorates rapidly in heavy rain.

2. When passive reflectors are used to enhance the runway, X band and Ku band are the best choices, with Ka band having slightly less range capability. Ranges of from 7 to 10 nm can be achieved at both X band and Ku band. However, the resolution at X band is not adequate to produce a radar map of the runway.

3. When beacons are used to enhance the runways, Ku band is desired over X band because of its better resolution. The beacon power required at either Ka band or V band is too large.

4. For the high ground avoidance function, a long pulse length (1.0 μ sec or longer) is desired. Both X band and Ku band give adequate performance. Ka band range is marginal and the V band range is poor.

5. For roll out and taxi assistance in Category III conditions, resolution requirements tend to favor the choice of the higher frequency bands.

6. Two alternatives are presented as summary suggestions:

   a) A combined ILM and HGA radar system with the following features...

      - o Ku band frequency
      - o 1 m antenna aperture in azimuth
      - o runways enhanced by reflectors
      - o 1.0 and 0.1 μ s pulse widths available

   b) A combined ILM, HGA, weather, and taxiway guidance radar with the following features...

      - o X-band frequency (possibly Ku band)
      - o 1 m antenna aperture in azimuth
      - o runways enhanced by reflectors or beacons
      - o 5.0 and 0.1 μ s pulse widths available

7. A cursory investigation of optical sensors indicated they do not offer much improvement over existing visual capability.